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A Life-Cycle Analysis of the Thermal Energy Transfer in Prototypical Air Force Office Building Construction Using Best Value Insulation Standards

Michael E. Canfield

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Michael E. Canfield, Capt, USAF

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A LIFE-CYCLE ANALYSIS OF THE THERMAL ENERGY TRANSFER IN PROTOTYPICAL AIR FORCE OFFICE BUILDING CONSTRUCTION USING BEST VALUE INSULATION STANDARDS

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Michael E. Canfield, B.S.M.E.

Capt, USAF

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Michael E. Canfield, B.S.M.E.
Capt, USAF

Approved:

Brent Langhals, PhD (Chairman)	Date
Alfred Thal, PhD (Member)	Date
Lt Col Clay Koschnick, PhD (Member)	Date

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Abstract

The United States Department of Defense (DoD) possesses over 560,000 buildings and structures around the world which require electricity to maintain and operate. The energy costs associated with the operations of these building is approximately $4 billion per year. Sustainable infrastructure management is a crucial opportunity to improve and establish a prudent, manageable, and successful DoD budget. This research identified, modeled, and simulated thermal energy-efficient standards in building construction in order to recognize the best value standards as opportunities for potential cost savings.

EnergyPlus and OpenStudio Building Performance Simulation (BPS) software was used to model the energy flow into and out of buildings to determine the annual energy costs for two prototypical DoD office buildings developed by the Pacific Northwest National Laboratory. The simulation inputs of building size, location, and insulation materials were varied to determine their effects on the energy cost. The results showed that exceeding construction code with R-15 wall insulation was consistently the most cost effective. Exceeding the construction code with R-60 roof insulation was more cost effective in the large facility located in the cold and mild climates. Lower than construction standard roof insulation was more cost effective in hot climates and in mild climates for the small facility.

The research results indicate that designers, engineers, and policy makers in the Air Force should consider facility life-cycle costs to lower annual facility sustainment costs. Accepting the construction code without performing an energy flow analysis of the facility during the design phase forfeits the opportunity to improve the life-cycle energy cost.

This thesis is dedicated to my fiancé. She has always supported me in all my professional endeavors and journeys with her love, understanding, and encouragement.

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Michael E. Canfield

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List of Symbols

Symbol	Definition
A	surface area
A_c	annuity for each period
E	total energy costs
ε	emissivity of the material
h	convective heat transfer coefficient of the material
I	initial cost
k	thermal conductivity of the material
LCC	total life-cycle cost
n	number of periods
O	other costs, if any
OM&R	total operating, maintenance, and repair costs
PV	present value
Q	heat (thermal energy
$\dot{Q}_{conduction}$	rate of conduction heat transfer over time
$\dot{Q}_{convection}$	rate of convection heat transfer over time
$\dot{Q}_{in}$	rate of thermal energy entering the system
$\dot{Q}_{out}$	rate of thermal energy flowing out the system
$\dot{Q}_{radiation}$	rate of radiation heat transfer over time
r	rate per period
Repl	capital replacement costs
Res	residual value after disposal costs
T	temperature
T_o	temperature of the environment
ΔT	difference in temperature between the two objects or fluids
U	internal energy
W	work (mechanical energy)
W_c	total water and other utility costs
Δx	material thickness
σ	Stefan-Boltzmann constant ($5.6703 * 10^{-8}$ W/m^2K^4)

List of Acronyms

A&E - Architect and Engineering
AFB - Air Force Base
AM - Amplitude Modulation
ASHRAE - American Society of Heating, Refrigeration, and Air Conditioning Engineers
BPS - Building Performance Simulation
DoD - Department of Defense
DoE - Department of Energy
EPS - Expanded Polystyrene
eQuest - Quick Energy Simulation Tool
FEMP - Federal Energy Management Program
FM - Frequency Modulation
GJ - Gigajoules
GUI - Graphical User Interface
HAP - Hourly Analysis Program
HVAC - Heating Ventilation and Air Conditioning
IBC - International Building Code
ICE - Indoor Climate and Energy
IECC - International Energy Conservation Code
IES VE - Integrated Environmental Solution Virtual Environment
IRC - International Residential Code
JB - Joint Base
kWh - Kilowatt-Hour
LCA - Life-Cycle Analysis
LCCA - Life-Cycle Cost Analysis
LEED - Leadership in Energy and Environmental Design
LPTA - Lowest Price Technically Acceptable
MARR - Minimum Attractive Rate of Return
MILCON - Military Construction
NIST - National Institute of Standards and Technology
NREL - National Renewable Energy Laboratory
NSRDB - National Solar Radiation Database
OMB – The Office of Management and Budget
PNNL - Pacific Northwest National Laboratory
RSI - R-Value System International
SI - International System
TRNSYS - Transient System Simulation Tool
U.S. - United States
USACE - United States Army Corps of Engineers
USAF - United States Air Force
USC - United States Code
U.S. EIA - U.S. Energy Information Administration
VAV - Variable-Air-Volume

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CHAPTER 1: INTRODUCTION

The concept of sustainability was brought into the global discourse for the first time when the United Nations published the Brundtland Report in 1987. The report states that there are environmental trends that "threaten to radically alter the planet, that threaten the lives of many species upon it, including human beings" [1]. Sustainability started as a response to climate change and the observed effects on the Earth's environment. The Department of Defense acknowledges that climate change is a threat multiplier to existing and emerging risks. Increased temperatures, rising sea levels, extreme weather, and changing precipitation are identified as some of the potential effects of climate change [2]. The global impacts may include societal instability, increased poverty, and additional conflict over resources. Resource constraints, water and food shortages, refugee displacement, natural disasters, and disease are additional factors from climate change that will increase and contribute to these impacts [3]. But climate change's root problem is not its impact, but rather the economies that have been built on unsustainable practices and unconstrained resource consumption. Moreover, sustainability has grown beyond the singular and sometimes polarizing issue of climate change. Instead, it encompasses an approach that can be applied to complex problems. It focuses on the broader interactions between resources, human society, and the environment to find long-term solutions. Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet their needs [1].

The current sustainability movement seeks viable solutions to a multitude of complex problems including but not limited to: addressing the epidemic of poverty within underdeveloped countries, implementing widespread environmental safeguarding, sustaining energy generation on renewable and clean practices, and reducing resource consumption and demand with a growing human population. Sustainability requires analysis from three central aspects: the economy, the environment, and the society [4]. The increasing pressures of operations and maintenance costs within constrained Department of Defense (DoD) budgets can also be addressed using the principles developed and applied from sustainability. Taking a comprehensive long-term approach to facility management can help meet current fiscal needs without limiting future operating, maintenance, and acquisition requirements.

Buildings are the basis of our civilization as they provide a built structure in which society lives, works, exchanges goods or services, is sheltered from weather, and even enjoys entertainment. Facilities are utilized and operated by society, funded and sustained with economic capital, and constructed and maintained with resources from our environment. Buildings are estimated to consume 70% of the nation's electricity [5]. The U.S. Energy Information Administration estimates that cooling, heating, and ventilation accounts for the largest energy consumption category in both the residential and commercial sector, approximately 24%. Reducing a building's energy consumption can clearly help reduce the largest factor in most building's operating expenses. This research aims to optimize and improve building energy efficiency to reduce the resource demand required for operating a building, which would in-turn reduce the impact on the environment and energy sources.

Background

The purpose of this research is to identify, model, and simulate thermal energy-efficient standards in building construction in order to recognize the best value standards and opportunities for cost savings. The motivation for this research problem is driven by facility energy usage and its large associated costs. High facility operating costs occur within many organizations while the facility sustainment budgets are becoming even more constrained. Meanwhile, the global economy's energy resource demands are increasing within a system dependent on finite energy fuel. This complex, global challenge provides the research context which addresses one facet of this enormous and interconnected problem. A long-term perspective is taken in this analysis to consider the total life-cycle cost of a building rather than simply the acquisition costs. An understanding of sustainability, asset management, and DoD infrastructure lays the foundation for the research's area of study.

Asset management is a key business practice to enable building energy efficiency. Asset management is successfully accomplished when organizational goals implement the intentional balancing of performance with costs, risks, and opportunities [6]. In simpler terms, it is the processes or decisions used to find something's most efficient economic life before it must be discarded. Asset management is often applied to infrastructure, facilities, or structures as a technique to optimize assets to meet organizational goals. The need for asset management is clear; facilities are expensive. The acquisition costs alone can seem large, but the hidden operations and maintenance cost is usually the most expensive part of a building's life-cycle [7]. To provide an example of this concept, a new phone may seem expensive. But this cost is small compared to the costs of activation fees, monthly phone plans, electricity required for power, transactions to buy phone applications, and accessories such as power cables, headphones, or cases. Asset management takes a holistic look at all costs, including hidden costs, to optimize the value of the asset for the owner. As budgets become more constrained, prudent management is imperative to reduce costs.

Asset management is an intentional, proactive approach to managing infrastructure. The alternative is a reactive approach that waits to respond to changes in the assets. The benefits of implementing asset management include: reducing operations and maintenance budgets, reducing the consumption of resources, and allowing better investment and management decisions to be made based on data [8]. Data-driven decisions are crucial to asset management effectiveness. Asset management can help an organization apply sustainability to their portfolio of assets. This research applies asset management principles to determine the optimal thermal energy efficiency standards for construction, thereby allowing an organization to meet the reduced operations costs and lowering energy demand.

The United States government and the DoD operate with limited resources. The DoD possesses 560,000 buildings and structures and the energy costs associated with the operations of these building is approximately $4 billion a year [9]. Sustainable infrastructure management is crucial to establishing a prudent and successful DoD budget. Effectively implementing building energy efficiency across the DoD enterprise will help achieve its energy plan goals to improve resiliency, optimize demand, and assure supply [10]. There are four lines of effort that support the DoD energy plan's goals: plans and operations, training and testing, built and natural infrastructure, and acquisitions and supply chains. Each line of effort discusses potential effects but also provides steps towards mitigation such as constructing underground utilities and effective firebreaks to make installations more resilient [2]. Research efforts focused on reducing resource demands aligns with the DoD lines of effort for operations, built and natural infrastructure, and acquisitions.

Sustainability, asset management, and DoD infrastructure reinforce the importance, the proven processes, and the application for this study. The research aims to model, simulate, and optimize thermal energy efficient construction standards for sustainable life-cycle building costs. The results compare the modeled construction configurations against local construction codes which contribute to the development of construction standards focused on improved sustainability instead of minimum safety requirements. The four research questions this study investigates are: (1) how can the Air Force receive the best value in facility construction from a life-cycle cost perspective with lowest price technically acceptable (LPTA) contracts? (2) do building construction codes specify the most cost-effective standards when analyzing a building's life-cycle energy efficiency? (3) will constructing to higher standards than the building code be more cost effective over a facility's life? (4) can an optimal insulation construction standard be developed for a prototypical Air Force office building?

Method

This research models the thermal energy flow in a building using computational modeling and simulation. The heat transfer rate across a building's physical envelop is the focus of the model. Building Performance Simulation (BPS) software models the energy flow into and out of a building using a large amount of user-input data, user-input parameters, and heat transfer formulas. Changing the input parameters, such as the construction material properties, affects the heat transfer formula outputs and a building's heat flow over time can then be analyzed. The parameters are bounded based on building construction common practices, construction experience, feasible standards, and the applicability for implementation by the United States Air Force.

The research is aimed at the Air Force minor construction program for facilities valued at approximately two million dollars based on the United States Code (USC) Title 10, Section 2805 [11]. The two-million-dollar financial limitation is based on the minor construction statutory limit required through policy compliant with Title 10 USC 2805. The National Defense Authorization Act for Fiscal Year 2017 amended Section 2805 of Title 10 USC to raise the threshold for unspecified minor construction projects from one million dollars to two million dollars [11].

Buildings maintain a steady state internal air temperature by balancing the heat flow through the perimeter with the heat or cooling added to the building. Minimizing the heat flow through the facility envelop will also minimize the heating or cooling required for the building to maintain a constant temperature. The heating and cooling energy also directly relates to energy costs for the building. The purpose of the BPS software is to model and calculate this heating and cooling energy cost. The first step is to simulate a prototypical office building while varying the key building parameters. A life-cycle analysis is then performed to calculate the life-cycle cost of each simulation configuration. Finally, an economic analysis is completed to compare each mutually exclusive construction alternative to identify the best value construction standard.

The dependent variable of the model is the heat flow over time across the building envelop. A building has a massive number of independent variables that affect the heat flow formulas. Many factors affect this energy flow to include the weather, the internal and external temperatures, the building shape, the building materials, the internal loads, and many more [12]. This research uses insulation type, building size, and building location to focus the research problem to a feasible study with meaningful results. The thermodynamic equations that influence the energy balance across a building envelope are very complex. Using the BPS software utilizes computational methods to simplify calculating these values. The building's energy cost can be calculated using a life-cycle analysis once the energy consumption is known. An economic analysis can then use the rate of return to compare mutually exclusive construction alternatives to quantify which configuration has the best economic value.

Application and Impact

The Department of Defense frequently uses the lowest price technically acceptable (LPTA) acquisition method. LPTA acquisition ensures the government receives the contract for the lowest price that meets the technical requirements of the work. However, technical sufficiency can be difficult to articulate and prove for buildings through the bidding process. Therefore, the Air Force relies on construction standards and codes as requirements in construction contracts to prove their technical acceptability. Third party codes are used in DoD construction such as the International Code Council's International Building Code (IBC). The IBC provides a baseline of standards within much of the United States to ensure safety for building construction. However, this baseline standard does not ensure the best value standards are utilized. Sustainment-focused standards enables construction to consider long-term resource and financial costs.

This research explores more stringent standards to enable long-term energy savings when implementing the LPTA acquisition methodology. The research results enable specific construction standards to be developed that the Air Force could implement to reduce building life-cycle sustainment costs. The research results could further be applied to construction in resource constrained locations. Reducing the energy demand of a base's buildings requires less resources to sustain these locations. Reducing the resources, transportation requirements, and logistics creates a synergy that also makes the bases more resilient. Sustainability within the military is best supported when it is cost effective and does not impact operational capabilities or capacity. Sustainable practices will be most successful in the DoD if it supports a lower budget, benefits operational capabilities, or increases operational capacities.

Research Scope

Building thermal energy flow is determined from operational use, environmental conditions, and construction characteristics. The mission and function of the organization dictates the operational usage. Optimizing operational use and reducing waste can result in many organizational benefits. However, this is constrained by the specifics of the building use, mission, and function. Additionally, the Air Force often prioritizes the operational capabilities that support its mission over the reduction in budget or energy resources. For these reasons, the operational function of the building was determined not to be a beneficial variable to manipulate in the scope of this research.

The location of the building determines the environmental conditions affecting the thermal energy flow. An environmental condition has large variations based on its location that have significant impact to energy flow. Weather data provides values for these variables that can be accessed with established databases. Six separate locations are modeled to capture the influence of location and climate on this model and simulation. A cold climate is represented by Minot Air Force Base in Minot, North Dakota and Ellsworth Air Force Base near Rapid City, South Dakota. A moderate climate is represented by Wright Patterson Air Force Base in Dayton, Ohio and Langley Air Force Base in Newport News, Virginia. Lastly, a hot climate is represented by Edwards Air Force Base near Bakersfield, California and Joint Base (JB) San Antonio in San Antonio, Texas. It is assumed that these six locations will provide sufficient climate variation to determine trends and the influence of climate on the model.

The focus of this model is the construction characteristics of the building. The construction of the building determines these characteristics and provides the basis for simulation and optimization. The BPS software allows manipulation of these inputs to allow analysis of the output. The model assumes uniform construction material qualities without defects or variation from typical values. The size of the building construction is targeted for the Air Force minor construction program. The United States Army Corps of Engineers (USACE) is required to manage larger projects under the Military Construction (MILCON) program. These larger projects have higher visibility and more direct management through techniques such as value engineering. As such, this research is not intended for this scope of construction. Air Force base-level engineers plan, execute, and manage the minor construction program. This scope provides a better opportunity for implementation of energy efficiency standards based on a long-term life-cycle perspective.

The literature review in Chapter 2 provides a summary of existing research pertaining to thermal energy flow through a building envelope and an overview of Building Performance Simulation (BPS) software. Chapter 3 discusses the methodology that was used in this study. Chapter 4 discusses the research analysis results, interpretations, and impacts. Finally, Chapter 5 summarizes the research and provides final recommendations.

CHAPTER 2: LITERATURE REVIEW

Chapter Overview

This chapter reviews the current literature on building energy efficiency and simulation. First, the focus and scope of the research topic is discussed to provide context to the relevant literature. An overview of the physics principles relating to heat transfer are explained to provide a foundation for the modeling and simulation. Next, the building components and the principles that influence heat transfer through the building envelop are identified for use in the modeling. Lastly, current off-the-shelf building simulation software are identified. Advantages and disadvantages are explored and the best applicable software for this research purpose compared.

Research Focus

The focus of this research is building construction scoped below two million dollars in cost for use as office space. This aligns with the motivation that the research results should be applicable within the Air Force minor construction program. The minor construction program is executed by the Air Force base-level engineers instead of centrally managed project execution such as United States Army Corps of Engineers (USACE). Due to the lower cost thresholds of this program, it receives a lower level of oversight providing a larger opportunity to benefit from this research.

The study is aimed to apply to either a new construction project or an office renovation project. The construction standards that provide the most cost-effective construction allow the base engineers to work with contractors and designers to ensure that the Air Force is building sustainable facilities. A construction program focused on sustainable policy reduces the energy demand required to operate the facilities each year.

The cost savings can then be re-invested in infrastructure, fund the procurement of other mission requirements, or reduce the burden on the taxpayer.

Thermodynamics Principles & Definitions

Thermodynamics must be studied and understood to analyze the energy efficiency of a building and to learn how thermal energy transfer occurs. Thermodynamics is the branch of physics that studies heat and temperature and their relation to energy, work, radiation, and properties of matter [13]. The first law of thermodynamics, conservation of energy, states that the total energy in an isolated system is constant. The first law of thermodynamics implies that the change in internal energy is equal to the heat supplied to the system minus the amount of work done by the system on its surroundings. The equation for the first law of thermodynamics is

$$\Delta U = Q - W \tag{1}$$

where

U is internal energy,

Q is heat (thermal energy), and

W is work (mechanical energy).

Defining a building as the physical system for study and applying the first law of thermodynamics given in equation (1) facilitates an analysis of the energies entering and leaving the facility. The building performs no work on the surrounding environment, so the mechanical energy transferred by the system is zero. Additionally, most facilities use Heating Ventilation and Air Conditioning (HVAC) equipment to keep a constant internal temperature. This provides a comfortable internal environment for its users, but it also establishes a steady state for the internal energy of this system. Under steady state conditions, the internal energy of the system remains constant due to a balance in heat loss and heat gained [13]. Deriving the first law of thermodynamics equation with these conditions provides an energy balance that can be described as [14]

$$\dot{Q}_{\mathrm{in}} = \dot{Q}_{\mathrm{out}} \tag{2}$$

where

$\dot{Q}_{\mathrm{in}}$ is the rate of thermal energy entering the system. This includes energy flowing into the building envelope and the energy being generated within the building.

$\dot{Q}_{\mathrm{out}}$ is the rate of thermal energy flowing out from the envelope into the outdoor space.

Equation (2) shows that the rate of thermal energy exiting the building is equal to thermal energy entering the building. Equation (1) and (2) allow a representation of the heat flow into and out of a system using formulas. This heat balance process can then be applied to a specific building as the system of interest. People, sunlight, geothermal heat flow, electronic fixtures, electronic equipment, and HVAC equipment all contribute to the energy flow into the building. Energy flow out of the building is the energy flow through the building's envelope into the environment. The building envelope is also defined as the systems boundary.

A temperature differential drives thermal energy flow as the environment strives for thermal equilibrium. Intuitively, a hot object will cool down to reach the same temperature as its surrounding given enough time. This is an example of a difference in temperature creating thermal energy flow in the same way as a pressure difference will create fluids to flow. Heat transfer occurs from a temperature difference in three forms: thermal conduction, thermal convection, and thermal radiation. Thermal conduction is heat transfer from direct contact, thermal convection is heat transfer from fluid movement, and thermal radiation is heat transfer from waves.

Thermal conduction is caused from an object's molecular collisions which transfer the energy from one object to another. The equation to represent thermal conduction is [13]

$$\dot{Q}_{conduction} = \frac{k * A * \Delta T}{\Delta x} \tag{3}$$

where

$\dot{Q}_{conduction}$ is the rate of heat transfer over time,

k is the thermal conductivity of the material,

A is the surface area between the two objects in contact,

ΔT is the difference in temperature between the two objects, and

Δx is the thickness.

Thermal convection is the energy transfer that occurs from heat transferring through a fluid. The actual physical flow of the molecules throughout the fluid causes the heat transfer in convection rather than molecular collisions, as is the case with conduction. When a fluid increases in temperature, the fluid becomes less dense. Buoyant forces then cause the fluid to rise, being replaced with the cooler fluid. This cyclical movement of the fluid transfers heat as the molecules moves. The equation to represent thermal convection is [13]

$$\dot{Q}_{convection} = h * A * \Delta T \tag{4}$$

where

$\dot{Q}_{convection}$ is the rate of heat transfer over time,

h is the convective heat transfer coefficient of the material,

A is the surface area of the heat transfer surface, and

ΔT is the difference in temperature between the surface and fluid.

Thermal radiation does not require a physical medium to transfer heat. Energy is transferred through electromagnetic waves which do not require direct contact to exchange heat. All matter above absolute zero emits some level of thermal radiation which can even travel through a vacuum. The energy transferred between two objects depends on the surface area, emissivity of the material, and temperature difference. The equation to represent radiation heat transfer is [13]

$$\dot{Q}_{radiation} = \varepsilon * \sigma * A * (T^4 - T_o^4) \tag{5}$$

where

$\dot{Q}_{radiation}$ is the rate of heat transfer over time,

ε is the emissivity of the material,

σ is the Stefan-Boltzmann constant ($5.6703 * 10^{-8}$ W / $m^2 K^4$),

A is the surface area of the emitting surface,

T is the temperature in Kelvin of the emitting object, and

T_o is the temperature of the environment.

Emissivity is a material property that quantifies the ability to emit or absorb thermal radiation. Emissivity is a dimensionless measure that ranges from zero to one. A perfect emitter, theorized as a perfect black body, has an emissivity of one. Kirchhoff's law states that a body absorbing and emitting radiation in thermodynamic equilibrium, the emissivity equals the absorptivity. This can be stated simply as an object's emissivity is equal to its absorptivity. This reveals that a material emits and absorbs thermal radiation to the same degree; therefore, a material that is a good emitter is also a good absorber [13].

Higher energy in the electromagnetic spectrum generally creates shorter waves and improves the penetration of the wave while lower energy creates longer wavelengths and improves distance. For example, watt-for-watt, amplitude modulation (AM) radio waves are lower energy and broadcast over a larger distance while frequency modulation (FM) radio waves are higher energy and will penetrate facilities easier. All wavelengths of light also carry photons of energy and can transfer heat. This thermal energy is considered lower energy on the electromagnetic spectrum and is relatively easy to reflect. It is especially critical in a facility to consider these principles in windows or exterior glass which can significantly contribute to energy transfer due to light. The principles of reflection, absorption, and emissivity are important to the transfer of heat, especially energy from the sun [15].

Thermal heat transfer encompasses all three modes of heat transfer: (1) thermal conduction, (2) thermal convection, and (3) thermal radiation. Modeling all three modes simultaneously can quickly become complex and computationally demanding. Instead, the three heat flow rates can be combined into a theoretical, apparent thermal conductivity. Convection and radiation are modeled with theoretical conduction coefficients to allow the combination of the three formulas. This allows the simplification of the convection or radiation formulas by modeling that all heat transfer occurs through conduction. The theoretical conduction coefficients are derived from equating the heat transfer from three methods to three conduction equations. The benefit of this visualization and modeling is the simplification of equations which allows modeling simulation software to perform with less computational requirements.

Construction Components in a Building's Envelope

The building envelope is the nomenclature for the physical separator between the conditioned space within a facility and the unconditioned space of the environment. It most often coincides with the exterior barriers of the building and it provides protection against unwanted heat, light, noise, water, air, and the external environment. It can provide three primary functions: (1) controlling the energy flow and matter flow between the facility and environment, (2) supporting the structural requirements of the facility to resist or transfer loads, and (3) improve the internal and external aesthetics of the building [16]. This research will focus on the first function of the building envelope as it is concerned with the thermal energy transfer.

The various construction components and materials that could contribute to a facility's building envelope are immense and immeasurable. However, the materials, systems, or components can be identified that most buildings have in common. Almost all buildings will have a combination of walls, roofs, windows, doors, insulation, and a foundation that contribute to the building envelope [17]. Each of these systems have sub-systems, components, and materials which influence the heat flow through the system and the entire facility. A review of each of these systems will provide an introduction into their importance and effect on modeling the prototypical building.

Walls provide thermal, acoustic, and moisture protection to the interior of the facility to facilitate a controlled and comfortable space. Walls can be classified as wood-based, metal-based, masonry-based, or a combination. They provide a significant portion of the surface area for a facility. Based on a study in Jordan, simply insulating the walls and roof with polystyrene insulation can reduce the energy demand in a facility by 76.8% [18]. Although this value will fluctuate significantly based on the specifics of the building envelope and facility geometry, it highlights the importance of the walls and roof on the thermal energy flow through a facility.

A typical wall structure involves a structural support component made of steel, wood, or masonry; an insulating material; a moisture control barrier; and a finishing material to provide aesthetics and consistent appearance [19]. The large surface area that walls typically represent in a facility make it a primary opportunity for thermal energy transfer savings; however, the physical geometry and interaction with other building envelope systems can diminish the expected savings from improvements. The cavity created between structural support elements, such as two-by-fours, can limit the size of the insulation installed. Additionally, how other building envelope systems interact with the support elements can provide avenues for the thermal energy to bypass the wall's insulating properties. Nevertheless, walls provide a critical area for improving the thermal energy flow through the building envelope.

A roof provides the top covering over a building and protects the facility from precipitation, sunlight, and varying temperatures. The roofing materials and design depend on its supporting structure, the distance it must span, the dead and live load weights it must convey, and the pitch or angle of the roofing system. Similar to a wall, the system comprises several sub-systems to include structural support members, insulating material, weatherproofing membrane or material, sealing components, and drainage [20]. The materials and roofing systems can extensively vary depending on its function and design considerations. Common materials for the structure of roofs include steel-based, aluminum standing seam, wood-based, masonry-based, and rubber-based.

Roofs can be classified as flat roofs or pitched roofs and can vary from simply supporting the basic live and dead loads to supporting thousands of pounds of utility system equipment. Despite the wide variation in roof systems, insulation remains an important sub-component for the roof. Similar to the walls, roofing systems can cover a large percentage of a facility's surface area. During the heating season, the heat within the internal conditioned space rises and transfers through the roof. This can be minimized with well-sealed and insulated roof systems. Conventional wisdom emphasizes adding insulation to the roof to improve energy efficiency, but this should be tempered with the principle of diminishing returns [21]. Heat will begin bypassing the roof structure by transferring through other building envelope systems using the principle of thermal bridging, discussed with further depth in this chapter within the 'other energy efficiency principles' section. Therefore, a life-cycle cost model should be implemented to properly analyze the appropriate roof insulation that should be applied prior to the decision of increasing or adding more insulation [22].

Windows and doors usually account for most of the wall openings in a facility. Although they are usually a much lower ratio of the surface area of a facility, they can cause heat transfer at 20 to 30 times the rate that it occurs through walls [17]. These wall openings can either be embedded in the structural system of the building to support its own weight or they can use a combination of structural components such as lintels, jambs, sills, etc. to transfer the loads around the openings. Window systems vary dramatically based on the quantity of natural light desired, thermal performance required, architectural or aesthetic preferences, and selected construction materials. Performance factors for windows include color and aesthetics, insulation, solar heat gain and light transmission, and acoustic properties [23]. However, the thermal performance of windows is nearly always less than that of the walls and roof. Methods for improving the standard window thermal performance include glazing, vacuum sealing, reflective or absorptive films, increasing the amount of window panes to add air gaps, and insulating the frames [24], [25]. Although the surface area may be lower for windows and doors, the low thermal resistance in these wall openings provide a critical path for a loss of thermal energy in the building envelope.

Building Insulation

The primary function of insulation is to reduce the thermal energy flow through the material in order to improve energy efficiency, air quality, and comfort. More materials and methods for insulation exist than can be comprehensively discussed in this literature review [26]. However, the common materials and typical methods will be discussed to provide an overview of insulation and its use within a building envelope. Additionally, as industry strives for more energy efficient practices, new insulation materials are being developed and implemented to achieve better performance [27].

Some of the typical insulating methods include using insulating batts, loose insulation, rigid foam boards, spray insulation, and structural insulated panels. This list is not all-encompassing but includes the most common methods for insulating a facility. Insulation batts or rolls, one of the most common form of building insulation, are pre-cut sections of insulation and strips of rolled insulation, respectively. They are commonly used in the walls and roof of a building and have a wide range of available materials and properties. Rolls and batts can be un-faced or faced with paper, foil, or plastic to assist with moisture and vapor control. The most common batt or roll materials include cellulose, fiberglass, plastic fibers, and mineral wool.

Loose insulation consists of small insulating particles that can be placed or blown into an area. The advantage of this method is that it conforms to the contours of the space, thus making it ideal for spaces with complex geometry, hard to reach areas, or locations with a significant number of penetrations. Common materials include cellulose, fiberglass, mineral wool, plastic fibers, polystyrene, and perlite. It is important to properly seal the area for air movement prior to using loose insulation or convection will still create significant heat losses.

Rigid foam boards provide a common alternative to batt or loose insulation. The rigidity of the board can make it easier to work with and it can be manipulated to a desired shape with common tools such as a circular saw. Common materials include expanded polystyrene (EPS) which is similar to Styrofoam, extruded polystyrene which uses plastic granules to extrude into a rigid board, and polyisocyanurate which is a thermoset plastic produced as foam. Moisture resistance is one significant advantage of this insulation method which causes it to frequently be used next to foundations and basements, as well as exterior wall sheathing. It can also be used in wall cavities, but more frequently other methods are more cost effective for this application. Fibrous rigid board insulation made of fiberglass, mineral wool, and perlite can also be used, but they are susceptible to moisture reducing their performance and causing them to be more frequently be used to insulate HVAC systems.

Spray foam insulation is a liquid foam that can be injected or sprayed in place to produce a high performing insulating material. The material properties for spray foam make it the most effective insulation used in building construction, but it can be challenging to install correctly. The liquid foam components must be mixed in the proper ratios to produce the desired material properties and prevent undesired off-gassing. The most common material used in spray foams is polyurethane which comes in closed-cell foams and open-cell foams, but some additional materials include cementitious, phenolic, and polyisocyanurate. When compared to closed-celled spray insulation, open-celled spray is less dense, easier to penetrate, and can have a spongy-like texture. It should not be installed where water can be an issue and is frequently used with renovation projects in existing walls. Closed-cell spray insulation is a rigid, dense material which offers even higher insulating properties than open-cell. It can be used for additional waterproofing and structural support in addition to its excellent thermal resistance. The disadvantage of spray polyurethane insulation is that it has a high cost and requires a specialized contractor for installation.

Many new materials and techniques are being used and developed to continue to improve insulation performance. New materials such as aerogels and dynamic insulation materials are also being tested and utilized in construction [28]. Structural insulated panel is one example of a developing technique being used in construction. These are prefabricated insulated structural elements that are used for walls, ceilings, floors, and roofs. This offers more uniform insulation by minimizing the thermal bridging across studs or standard structural elements. Structural insulated panels require prior coordination between the designer, manufacturer, and construction contractor, but it can offer improved performance when executed properly.

Other Energy Efficiency Principles

Several other construction principles influence the energy flow through the building envelope. Some of these include the building shape and size, the building orientation, the internal loads, the HVAC system, and thermal bridging. The facility shape, size, and orientation all affect how the building interacts with the outside environment. The surface area that creates the boundary between the outside environment and the building envelope, in addition to the incident angle of direct sunlight, are two very important building properties to thermal energy gains. Optimizing the size, shape, and orientation can passively reduce the energy costs without increasing the costs for construction [29]. These factors must be considered and controlled during the design phase prior to construction.

The internal loads and HVAC system contribute to the internal heat gains within the facility. These are operational factors that can dramatically affect the thermal heat flow through the building envelope. The latent and sensible heat gained through personnel and equipment must be incorporated when sizing the HVAC system to ensure that the system can adequately control the conditioned space. The internal temperature set point, amount of ventilation, and estimated infiltration must be considered to adequately select the appropriate HVAC system [30].

Many additional energy efficiency strategies have been developed to reduce the effects of energy loss through the building envelope. Some of these initiatives include green roofs, photovoltaic roofs, radiant-transmittive barriers, evaporative cooling, thermal mass or phase changing materials, precision building to increase air tightness and decrease infiltration, facility shading, and skylighting [31]. These potential energy savings methods are not discussed in depth since they are often situational to the facility and climate. Although they can be effective in reducing the energy demand for a specific building, they are not widely applicable to all facilities or climates. This makes these methods difficult to include in this broader research scope aimed for implementation across the entire Air Force enterprise.

Lastly, the principle of thermal bridging needs be understood to properly design a facility and improve the thermal energy flow through a building envelope. Thermal bridging is the principle that more heat flows through a conductive object if it is more conductive than the materials around it. Electricity moves through the path of least resistance and thermal energy flow follows an analogous principle. The impact of this principle is that a building with an extremely well insulated wall and roof will still lose significant heat through thermal bridging caused by poorly insulated areas such as windows and doors. This principle creates a diminishing return when adding insulation to a building envelope component because the heat will find another component with lower insulation to primarily flow through. Additionally, a single building envelope system can also have thermal bridging such as wooden studs that provides an alternative path around insulation in the wall cavity or uninsulated window frames providing a thermal bridge around high performance window glass [32]. Significant thermal bridging can also create additional problems such as undesirable condensation and moisture within a wall system [33]. The result of thermal bridging is that no area in a building envelope can be neglected in order to achieve the best thermal energy efficiency. Understanding thermal bridging is critical to analyzing a building envelope and reducing the thermal energy flow for a facility.

Introduction to Building Performance Simulation

This research aims to improve energy efficiency standards for the Air Force which would reduce its buildings' annual energy costs. Existing Building Performance Simulation (BPS) software provide the means for modeling and simulating without the need to recreate, develop, or derive the heat transfer algorithms. Prior to an analysis of the energy efficiency of construction standards, the research must: (1) evaluate off-the-shelf BPS software, (2) select the best BPS software for the application of this research in energy modeling, and (3) implement the selected BPS software to collect data with varying building characteristic parameters.

The total life-cycle cost of a building can be reduced by identifying and optimizing energy efficient construction standards focused on long-term costs [34]. This study hopes to develop construction standards focused on sustainment rather than minimum code requirements. Low-Bid Technically Acceptable (LPTA) contracts are a frequently used DoD contract type that focuses primarily on initial acquisition costs rather than total life-cycle cost. Sustainment focused standards would enable the Air Force enterprise to receive cost savings despite the LPTA acquisition methodology. In order to develop a sustainment focused construction standard, not only must the acquisition cost be considered but also the annual sustainment cost. The annual sustainment cost depends on operations costs, energy costs, and building repair costs.

The annual energy costs are the focus of this research since the operations and repair costs are assumed to be primarily dependent on the building function and not the construction materials [35]. The construction material can be a key building parameter of the model which will directly influence the annual energy costs. Moreover, construction material standards can significantly affect the thermal energy flow within a building and affect the energy costs [36]. Focusing on the construction material in the model links the energy costs with the construction standards.

Selecting the appropriate analytical tools is crucial to research success. Emphasizing finding the correct BPS software to use for the building modeling was a crucial step to ensure the appropriate tool was selected. Prior to modeling, an analysis and initial demonstration was performed of all the considered BPS software. The selected BPS tool was then able to be applied to the main research effort to analyze building energy sustainment costs.

Building Performance Simulations (BPS)

Building Performance Simulation (BPS) uses computer simulation and modeling based on physics principles to quantify building performance. BPS is used in the design, construction, operations, and evaluation of buildings. Using BPS software during the design phase of a building can reduce the energy demand on buildings by as much as 35 to 47% [17]. It ties the physical characteristics of a facility to a model. Building performance results are determined from the changes in the building inputs. BPS is an expansive field that includes many sub-domains with some being thermal, lighting, acoustical, or air flow simulations. This research was concerned with the thermal simulation sub-domain since it has the most direct impact to energy costs.

Hundreds of BPS software tools have been developed since it was first applied in the 1960s to simple, steady-state, and single system applications [37]. BPS software tools have been developed for use in government, industry, academia, performance ratings, and design. As the domain grew, the application of BPS tools expanded to general geometric modeling, building envelope properties, HVAC sizing and zone loading, lighting and daylighting, air quality and flow, infiltration and ventilation, electrical and equipment loading, renewable energy sourcing, and many more. The sub-domain of thermal simulation applies to this research as an application of the building envelope. Thermal energy loss through the building envelop can be directly quantified as the required energy necessary for the HVAC system to keep the building at a steady state temperature. The internal HVAC distribution, zoning, and energy flow are less relevant since the overall sustainment cost is the focus of this research. Only the energy leaving the system affects the overall sustainment cost, not the energy flowing from one room to another within the defined system.

Numerous BPS software programs had to be narrowed down to only a few that could be considered for use in this research since time constraints and practicality prevented analyzing every tool. Previous research was used as the primary criteria for reducing the potential BPS candidates to an adequate number to evaluate [37], [38]. The intent was to perform an initial evaluation on approximately ten BPS software that could be suitable for this research. Then a deeper comparison, evaluation, and analysis was performed on the best candidates, ideally applied to four or less. The software evaluation criteria included software that is prominent within previous research, common in actual use, considered to have accurate simulations, and most importantly suitable to implement in this specific model application. The four BPS software that were selected for the deeper evaluation included the Quick Energy Simulation Tool (eQuest), EnergyPlus, Trace 700, and Integrated Environmental Solution Virtual Environment (IES VE). Other software considered were Carrier Hourly Analysis Program (HAP), Transient System Simulation Tool (TRNSYS), Ecotect, AECO Sim, and IDA Indoor Climate and Energy (ICE). All nine BPS software were well regarded within the domain, applicable to evaluate energy flow through a building envelope, and used in relevant, prior research [37].

EQuest uses the DOE-2 energy analysis program or ‘engine’ to perform its energy simulations based on input weather data. Both eQuest and DOE-2 were originally developed for the Department of Energy (DoE). However, they have since been utilized throughout industry, government, and research. Version 2.2 of the DOE engine and version 3.65 dated 4 October 2018 were evaluated in this research. EQuest is a free software open to anyone for use. EQuest is one of the most prevalent BPS due to its age, open accessibility, zero cost, and positive reputation from the Department of Energy [39].

EnergyPlus has many similarities to eQuest. It was also developed by the Department of Energy, using the same DOE-2 engine as eQuest. It builds on the DOE engine while providing additional modeling capabilities and features. It is updated semi-annually with version 9.1.0 dated 27 March 2019 used in this research. Several additional programs have been developed to improve the interface between the user and EnergyPlus. Two more prevalent programs considered were OpenStudio and DesignBuilder. Neither of these programs change the input or output of EnergyPlus, but rather make the BPS more user friendly for the analyst. EnergyPlus and OpenStudio are also free to use while DesignBuilder has a 30-day free trial. EnergyPlus is free, open-source, and cross-platform causing it to continue to gain in reputation and use. DesignBuilder costs between $595 and $1995 plus tax for the software in addition to an annual licensing fee, but it offers a 30-day free trial of the full version.

Trace 700 was developed from the Heating Ventilation and Air Conditioning (HVAC) manufacturing company TRANE. As a HVAC system designer and provider, TRANE developed Trace 700 as a BPS focused on the design and analysis considerations for an HVAC system. Trace 700 was developed to assist designers in comparing energy and economic impacts of alternatives in HVAC systems. Version 6.3.4 dated 31 March 2018 was evaluated in this research. Trace 700 leverages the parent company’s resources providing a technical HVAC focused BPS. Trace 700’s reputation is consistent with TRANE’s high reputation in the HVAC industry.

IES VE is developed and offered from a company in the United Kingdom founded in 1994. The software initiated from research in 1979, but the commercially available software was not available until 2000 and it was not launched in the United States until 2003. IES VE has a suite of individual applications that can be chosen and applied to the central data model. The applications allow for customization based on the analysis being performed. The price for the software varies depending upon the applications selected. A free 30-day trial is offered to students but requires a validation process. The software continues to have periodic updates and has gained in reputation as a prominent BPS. IES VE has won awards from Leadership in Energy and Environmental Design (LEED) and the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE).

The other BPS considered included Carrier HAP, Trnsys, Ecotect, AECO Sim, and IDA ICE. These programs were identified in reviews and research as also being prominent BPS software. However, they were not determined to be as promising a fit for this research as eQuest, EnergyPlus, Trace 700, and IES VE. Many BPS are specialized for a specific application and this research requires software that is easy to learn and modify without significant training. The software must be intuitive and user friendly to allow the tool to be quickly implemented and adapted to the research question. Specialized training or a large learning curve was not desired to allow progress in the research. Although they can be considered equally capable to those previously mentioned, these additional BPS programs were not as suitable to a short research timeline. Many of these other BPS are better applicable to industry or business implementation rather than research. Additionally, the focus of many of these BPS programs was not placed on the sub-domain of thermal simulation or not suitable for the building envelope analysis required. For these reasons, these other BPS were not considered for the deeper comparison.

BPS Comparison

eQuest, EnergyPlus, Trace 700, and IES VE programs were downloaded, implemented, and compared to determine their potential use. Each software could be viable to apply to this research with its own strengths and weaknesses. However, the comparison was necessary to select the most suitable software in order to meet the objectives for this research. The user-interface, customization subtleties, and focus of each software was experienced through experimentation and first-hand simulations with each software. The justification for the final BPS software selection was then based on these personal demonstrations of each software.

EQuest is a well-established, known tool with trusted results. The computation speed and time required for the simulation is low, thus allowing almost instantaneous simulations for simple buildings. The simulation uses one-hour increments for the weather data and simulation. The building characteristics are edited using the 'wizard GUI' design tool. The input parameters involve over 40 separate screens which can be challenging to navigate without being familiar with the program. The overall interface is less intuitive than the other BPS software. The internal zoning capabilities are less than the other BPS software, but this is not as relevant for building envelope analysis. This program is great for initial design considerations and comparison of alternatives. The largest concern for application to this research was the learning curve with the raw interface and customizing a facility's structure.

EnergyPlus uses the same DOE engine as eQuest but performs the simulation using 15-minute increments instead of an hour. The smaller simulation increment combined with improvements to the modeling provide a very accurate BPS output. OpenStudio and

DesignBuilder improve the user interface and make the software navigation significantly more intuitive. OpenStudio was used since it was free to use. Both programs are aesthetic without changing the quantitative output of EnergyPlus. The improved interfaces also enable the simulation to be more transparent and easier for additional research to replicate the simulation. The settings and inputs are just as complex as the other BPS software, but it enables customizable modules which are more intuitive. When compared to the other BPS, EnergyPlus is more accurate, focuses on the heat balance building perimeter, allows for intuitive customization, and is open source. The largest concern for this BPS application is the learning curve associated with the building geometry input which uses an open-source software plug-in FloorspaceJS. This software is comparable to the building editors in the other BPS such as SketchUp, but FloorspaceJS software was less familiar.

Trace 700 is HVAC focused with an emphasis on heating and cooling load calculations, HVAC sizing, and system controls. However, the building envelope loads must be calculated to properly size the HVAC system requiring the program to fill many additional BPS capabilities. The interface is extremely easy to navigate with it being the most intuitive of the BPS software. The interface is well oriented with screens consisting of windows, tabs, and drop-down selections that are familiar to computer users. Trace 700 is fantastic when using the pre-populated options, but more difficult to customize.

The HVAC detail was in-depth and includes ducting, plumbing, Variable-Air-Volume (VAV) boxes, and controls. The software also included equipment such as chillers, pumps, cooling towers, and heaters. The HVAC level of detail was more than the level required for this research, but it would be very valuable for an Architect and Engineering (A&E) design application where these individual items and components must be selected.

The focus of the BPS was clearly HVAC sizing and not the building envelope. The output focused on the maximum loads required for sizing rather than the total cumulative loads required for energy loss balancing. The largest concern with this BPS applied to this research was the primary focus not being in the proper BPS sub-domain or application. Although the software produces the necessary output and provides an intuitive interface, many of the HVAC inputs were not required for this research and customization is more difficult in Trace 700.

The IES VE software was developed with sustainability and reducing building energy consumption as the primary driver. The software grew from a PhD research effort and became available software after decades of development. The interface is more complicated and less intuitive than the other BPS considered. The application-based interface allows selection of capabilities to enable only the analysis desired. Unlike Trace 700 where the focus is HVAC central, IES VE allows the analyst to choose the focus. The learning curve was greatest for this software over the others considered. The free trial required a validation process for students or researchers which was not as straightforward as advertised. It was challenging to know which applications to select and how to use each application without training. The largest concern with IES VE when applied to this research was the complicated interface and numerous applications available. Without proper training on the software, the risk that it would not be an ideal fit for the research was too high when other alternatives existed.

Chapter Summary

This chapter began exploring the context and focus of this research. The research scope is narrowed to construction of facilities within the U.S. Air Force minor construction program. Reducing the sustainment costs of facilities through energy efficient construction standards defined the context of the research. Thermodynamic principles lay the foundation for determining the thermal energy flow throughout a building. To determine the cost associated with energy efficient standards, the physics controlling the energy flow must be understood. Convection, conduction, and radiation were overviewed to provide a working understanding of these principles. Next, the critical components in a building envelope were discussed. A building envelope is complex with each parameter interacting to create heat flow. This research focuses on the building shape, size, and insulation to provide feasible bounds on the model variables. Lastly, BPS software was presented as an off-the-shelf solution to heat balance algorithms. Utilizing existing, proven software prevents recreating the algorithms required to model and simulate heat transfer in a building. Instead, nine existing BPS software that are commonly used in industry were considered for this research. The advantages and disadvantages of four were extensively analyzed. Chapter 3 will provide a BPS selection for this research in addition to overviewing the methodology for simulating the thermal energy flow in a building.

CHAPTER 3: METHODOLOGY

Chapter Overview

This chapter describes the methodology for determining the total life-cycle energy cost of a building. The methodology is divided into three parts. In Part I, the BPS software is selected from the four programs compared in Chapter 2. In Part II, the settings and inputs are described for the BPS software. An overview of each section in the BPS software provides the means for others to repeat these simulations. More detail on the settings can be viewed in Appendix A and Appendix B. In Part III, the input variables that are manipulated are described. This part describes the changes between simulations that provide the data that is analyzed in Chapter 4.

Part I: Selection of BPS Software

The decision criteria considered for the BPS in this research were the simulation's accuracy, interface intuition, customization, cost, sub-domain focus, and ease to implement. The EnergyPlus BPS software with the OpenStudio interface software was selected for this research. However, all four BPS software being compared were identified as viable alternatives suitable to implement in this research. The primary justification for this selection was the intuitive interface and ease for customization. Although Trace 700 had the best interface, the emphasis of Trace 700 was too focused on HVAC. It provided many superfluous features and required many additional details that were only important to the internal interactions of the building such as zoning and system specifications. The building heat balance through the building envelope was the focus of this research which was better reflected with EnergyPlus and eQuest [40]. EnergyPlus provided a better and more intuitive interface than eQuest. Additionally, EnergyPlus provides a more accurate simulation having built upon the eQuest software [38]. EnergyPlus is a proven, accurate software used frequently in thermal energy research shown to have less than 10% error in accuracy when compared to actual facilities [41]. EQuest, EnergyPlus, and OpenStudio also have the benefit of being free and opensource. Although not the primary criteria, this benefit was a consideration. Lastly, the interface in OpenStudio and EnergyPlus allows for easier replication of the simulation which is important for validation of the research results. The repeatability of the overall research was a significant consideration when determining the appropriate selection.

Repeatability is one of the main decision criteria that aided in selecting EnergyPlus as the BPS software for this energy simulation. Repeating a building simulation can be very challenging due to the complex interaction of numerous parameters in the heat balance algorithms, energy flow modeling, weather and site data, and building model [42]. The large quantity of inputs, the various ways to model the building, and the environment interactions contribute to the numerous BPS software available. The methodology section of this paper provides the settings and input for each section of OpenStudio. The reason for providing these settings, inputs, and justifications is to enable other researchers to repeat this method using the same software and inputs. Additional details for the software settings may be found in Appendix A and Appendix B.

The focus on the building envelope's total energy flow is an important qualification for this simulation and research [43]. The model is not concerned with the internal energy transfer or zoning within the building. Although these are crucial to maintaining a comfortable and consistent temperature profile throughout the building, it has a minimal impact on the energy flow to the outside of the facility. Proper facility design must address these zone or energy flows between rooms, but this research is more concerned with the overall building energy. The error in the heat balance caused by this generalization is considered negligible since each simulation will be using this same assumption. Testing of EnergyPlus has shown the accuracy between a model and experiment to be within one to two degrees Celsius when used to predict temperatures due to heat flows [44]. The primary key building parameters considered with this building envelope focus are the building shape, building size, site location, environmental temperature, internal temperature setpoint, wall composition, roof composition, foundation composition, window composition, occupancy, and internal equipment loads. The three key building parameters varied in this research are the building shape, building size, site location, wall composition, and roof composition.

Part II: OpenStudio Settings and Inputs

The OpenStudio interface is organized into 15 different screens or sections which then have tabs to further subcategorize some of the sections. Each section has input parameters for the building model or simulation that enable the analyst to input the specifics of their situation. The OpenStudio model uses modules throughout the interface to layer the inputs for organization and use. The program comes with many pre-populated modules, allows customization of existing modules, and provides the option to create new modules. Wherever possible, the existing modules were used to improve the repeatability of the simulation. Since the software includes so many options and can be complex, each input was documented visually in Appendix B. Appendix A summarizes the OpenStudio settings in a table for a more concise format. Table 1 provides a portion of Appendix A to provide an example of the BPS setting documentation.

Table 1: Example of Appendix A - Summary of inputs for OpenStudio to demonstrate the software capabilities and enable simulation repeatability

WBS	Category Name	Input Name	Input
1.1	Weather	Weather file	USA_OH_Dayton-Wright.Patterson.AFB.745700_TMY3
		ASHRAE Climate Zone	5A
		Calendar Year	2020
1.2	Life Cycle Costs	Analysis Type	Federal Energy Managemt Program (FEMP)
		Analysis Length	25 years
		NIST Fuel Escalation Rates	Yes
		NIST Region	MidWest
		NIST Sector	Commercial
1.3	Utility Bills	N/A	N/A
2.1	Schedule Sets	Default Schedules	Office Small Activity Schedule
			Office Small Building Occupancy Schedule
			Office Small Building Light Schedule
			Office Small Building Equipment Schedule
			Office Small Infiltration
2.2	Schedules	Office Small Activity Schedule	120 Watts/person
		Office Small Building Occupancy Schedule	Step starts at 0600 peaks at 0800-1600 with a dip at 1200 for lunch hour. Gradual step down after 1600.
		Office Small Building Light Schedule	10% emergency lighting assumed. Step starts at 0500 peaks at 0800-1700 with a more gradual step down. Affected with the lunch hour.
		Office Small Building Equipment Schedule	30% baseline use. Peaks at 0700 until 1700 with one step at 1800. Affected with the lunch hour.
		Office Small Infiltration	Value of 1.0 throughout the day

The first section in OpenStudio addresses the weather data required for the simulation. Weather data was downloaded from https://www.energyplus.net/weather where EnergyPlus has combined over 20 different reputable weather data sources. This research used 'typical meteorological year 3' weather data which is derived from the National Solar Radiation Database (NSRDB) archives. The National Renewable Energy Laboratory (NREL) manages these data files by ensuring their accuracy and improving the data quality. This data provides hourly weather data for each day in a typical year. This does not provide the extreme weather values that are often required for HVAC sizing and system design. These extreme conditions are summarized as design days, but design days were not used for this research. Instead, the BPS software uses the weather data as the basis of its simulation. Since the weather is not completely predictable, the simulation uses the typical weather data and the recorded variations to simulate several iterations of the built model. The results from the weather simulations are included and summarized in the results section, which can be seen in OpenStudio section fifteen.

ASHRAE is an organization that provides standards and guidelines for HVAC and mechanical engineering. ASHRAE has developed environmental climate zones for geographic locations within the United States. A map of these climate zones, see Figure 1, was used for the input in the weather section of OpenStudio.

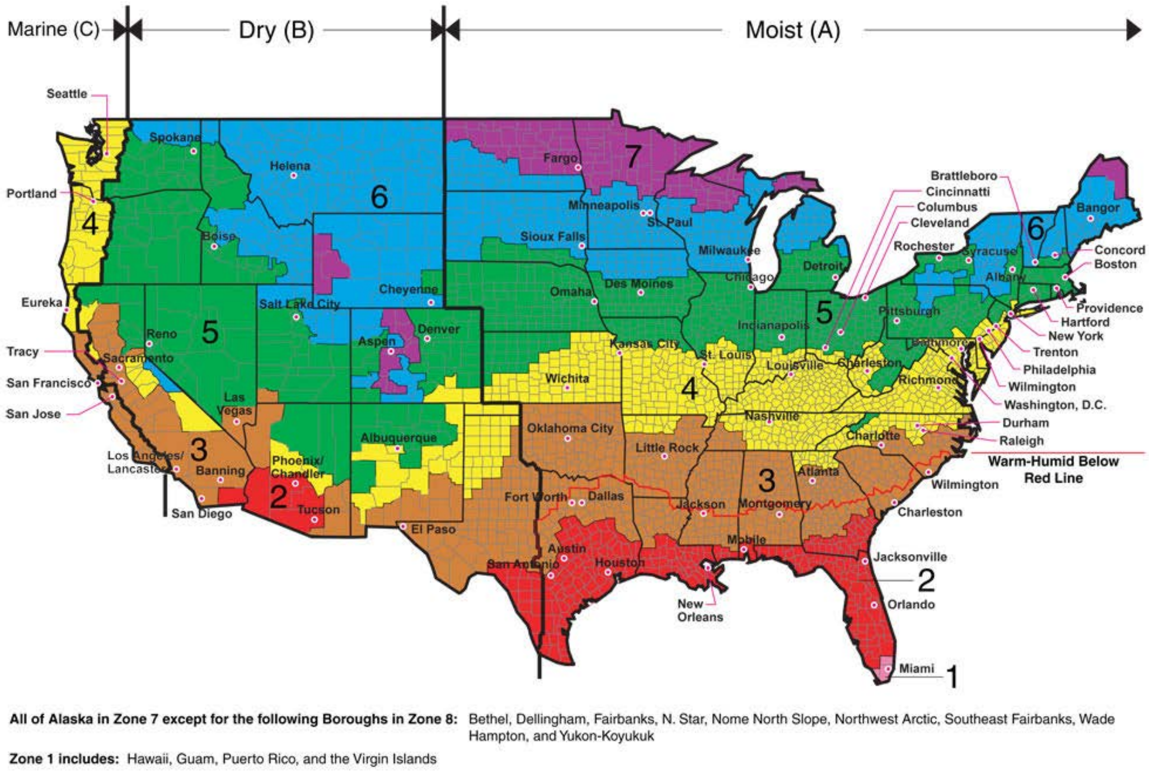


Figure 1: ASHRAE Climate Zones

The weather section’s sub-section named life-cycle costs allows the customization of the simulation’s life-cycle analysis parameters. The Federal Energy Management Program (FEMP) provides guidelines for this type of analysis [45]. The default setting was selected for this simulation. The analysis length is set to 25 years as an average time required before a large building renovation. Han et al. [46] reported an inflection point at 25 years in his research which used EnergyPlus and DesignBuilder BPS with genetic algorithms to optimize building life-cycle cost using building components. Twenty-five years was also chosen because the building components will be at the end of their designed or specified lives and should be replaced [47]. This is especially true in the Air Force where operational considerations often drive renovations for function changes. For some individual component context, the life expectancy of a typical roof is 20 to 30 years, a window is 15 to 20 years, HVAC and boilers are 10 to 20 years, and insulation is 20 to 30 years [48]. The National Institute of Standards and Technology (NIST) is a reputable organization that provides various standards. The default to use NIST for fuel escalation rates over this life-cycle analysis was accepted. The commercial NIST sector was chosen since this sector includes office space. Utility bills were not considered since actual building performance data was unavailable and was estimated based on the site's location.

The second OpenStudio section contains the schedules that the building operates. This includes the HVAC operations, personnel flow, lighting schedule, equipment schedule, and infiltration. These categories do not operate at a constant rate in a daily or weekly schedule. Instead, the loads from these categories fluctuate depending on the building use. A typical HVAC system used in a commercial setting such as an office space will operate in some capacity all day, so a 24-hour HVAC setting was used in OpenStudio. It may not be actively cooling or heating the space, but the system will usually use the fan to provide a minimum air flow required for air quality and building equipment. Most large HVAC systems will have variable air flow or fan speeds to improve the energy efficiency of the system and prevent it from operating at 100% all the time. The system controls will vary these air flows based on the minimum loads or air flow required.

The occupancy for an office space will follow typical work hours. Some personnel will come in early and steadily increase until all personnel arrive for work. The peak personnel will remain consistent except for the lunch hour where it will drop. Finally, the personnel will begin to leave the building as work ends and they return home. The afternoon decrease is seen to be lower than the arrival rate since some personnel must work late. The OpenStudio schedule settings provides a means to model the flow of personnel. Personnel also drive the use of lighting, equipment, water, and outlet electricity which all follow this same profile curve to some degree. The light schedule assumed that 5% of the lights would always remain on as emergency lighting. Electrical loads assumed a 30% and 40% baseline due to equipment, computers, HVAC, and other building items that always demand electricity regardless of occupancy. The two baseline values correspond to electrical outlet demand and electrical demand, respectively, which are split since occupancy has a more direct impact to outlet use. Infiltration is modeled with a constant that is based on the tightness of the building construction which is then set to a 100% schedule to show the constant infiltration.

The third OpenStudio section enables the modeling of the building construction. This section allows the varying of the materials and material properties used in construction, thus making it the most relevant section to explore the research questions. Most construction surfaces are a composition of various layers of building materials. This section allows a building to be separated into construction surfaces such as walls, windows, roofs, foundations, and many more. Each surface may then be further separated into individual materials such as paint, gypsum board, wooden two-by-fours, cellulose insulation, etc. Lastly, each material may have its properties adjusted or customized to reflect the modeled building material qualities. The building construction consisted of two prototypical office building constructions to model typical office space.

The fourth section includes the internal loads that would affect the energy required to maintain a constant temperature. The internal loads considered for this simulation included the sensible and latent heat generated from occupants, the heat generated from lighting, and the heat generated from electrical equipment. These loads follow the applicable schedules developed in section three. The fifth section addresses internal space types useful for internal air flow, zoning, and ducting which is not required for this simulation.

The sixth section provides the geometry of the building to include its size, shape, and orientation. It also communicates to the software how the surfaces defined in section three interact with one another. This is another crucial section to correctly and accurately define the building model for the BPS software. OpenStudio uses the FloorspaceJS program to develop the building geometry. The prototypical building used in the analysis must be created within this program for OpenStudio to use.

The seventh section provides building attributes that are applied to the geometry defined in the sixth section. Many of these features are not relevant to this application since the internal energy flow is a secondary concern in this research. One relevant setting is the nominal floor-to-floor height which is required for zoning and air volume calculations. Even though multiple zone analysis is not being performed, this must be defined to separate the conditioned space from the plenum, which is discussed in the ninth section. The eighth section is the spaces which defines the space types designated in section five. The defaults are appropriate for this section which allow for the two space types of a single zone and a plenum. This section would need to be detailed if the research is concerned with the internal air flows or zoning.

The ninth section applies thermal zones to the space types defined in section eight. Since the internal zoning is not a concern for this simulation, the building may be separated into two categories, conditioned space and unconditioned space. The conditioned space is designated as ‘single zone’ and includes the locations of personnel or equipment sensitive to temperature and humidity. The unconditioned space is designated as ‘plenum space’ which should be everywhere else for this simulation. A plenum is a part of a building that allows for air circulation. This is unconditioned space that is frequently seen above a drop-down ceiling, in utility corridors, or in the space between the ceiling and floor. This section also allows for the setpoints of the HVAC fluid temperatures used in the HVAC system. These temperatures were left at the default values from the prototypical model which are typical for most HVAC systems.

The tenth section defines the HVAC system layout used in the building. A typical centralized, packaged HVAC unit was used with heating and cooling coils, distribution ducting, and a supply air mixed with outside air to increase air quality. This is typical in Air Force office spaces, although a few older bases have centralized plants for steam such as Wright Patterson, AFB. Since these are in the minority, centralized plants were not considered for these simulations. However, the trends in the results and decision-making principles would remain the same regardless of the energy source.

The eleventh section allows the analyst to toggle the output variables in the simulation result. There are 571 possible output variables with the default only having 25 turned ‘off’. These 25 all related to an aspect of zoning, which was not a concern for this research. The 546 output variables remaining ‘on’ were used for this simulation. The consequence of extra output variables is a longer summary report in section fifteen. However, since only the result summary values relevant to the research question are used, no harm is created from keeping these variables 'on'. Using the defaulted 'on' values saves the time required to understand how the algorithm uses each of these output variables.

The twelfth section sets the conditions for the simulation parameters. The defaults for the simulation were used. This section includes important settings such as the HVAC sizing factor, simulation timesteps, convergence parameters, simulation iterations, and algorithm selection. HVAC systems are typically sized beyond the maximum loads required. This ensures an operational factor of safety to prevent the HVAC from shutting down when the designed conditions are exceeded, such as may be experienced during an uncommonly hot day. However, oversizing an HVAC system affects the performance and makes the overall system less energy efficient. The default sizing factors in OpenStudio are common industry practice values.

The simulation timestep determines the time used for each datapoint in the simulated energy balance. Decreasing the amount of time between each step increases the algorithm accuracy, but it also increases the complexity and time required. This tradeoff between accuracy and complexity is frequently observed in simulation and modeling. The convergence parameters control when the simulation algorithm determines that it has reached an optimal solution. More stringent parameters will require additional iterations. The simulation and iterations are required since there is uncertainty in weather. The simulated weather used in the algorithm is based on the historical data and the probabilities of typical weather experienced based on calendar day. Lastly, EnergyPlus allows the analyst to select from several different algorithms used to model the heat transfer equations.

The DOE-2 algorithm was selected since this was the algorithm originally intended for EnergyPlus. The thirteenth section addresses additional measurements that can be customized into the simulation and results. This section was not used for this research.

The fourteenth section runs the simulation. This section does not have any inputs but requires the analyst to click the run button. The fifteenth and final section provides the results summary from the simulation. This provides the output from the simulation and modeling. It provides an extensive report with many extraneous details since the output variables in section eleven were not filtered. This research is concerned with the total annual building energy use, which will be discussed more in Chapter 4. For more information on the settings used in each of these sections, see Appendix A and Appendix B.

Pilot Study Simulation Results

The purpose of using a BPS software is to determine the building's total energy use per year. The annual energy value is the total amount of energy the facility requires from a utility provider to operate for the year. The energy cost that utility companies charge customers in this region can be converted to the annual sustainment cost for the building. When the construction materials are varied, the annual sustainment costs can be compared. A comparison of the total life-cycle costs of the facility alternatives can also occur when the acquisition cost for constructing with these materials is also included.

The OpenStudio results section provides the reports from the Energy Plus simulation. There are numerous different results that can be used for a multitude of applications beyond this research. However, this research is primarily concerned with the total annual energy required to maintain a constant internal temperature. The 'total site energy' with units of Gigajoules (GJ) provides the value for the total annual energy required for the building sustainment.

The OpenStudio report also provides the site to source energy conversion factors. This is relevant to a life-cycle cost analysis whose boundary conditions are not limited to the facility but instead consider the energy generation. However, this research only looks at the life-cycle cost from the perspective of the building user or the Air Force, not the overall energy impact to the environment.

The OpenStudio result summary table should be used which includes end-users and provides subcategories for the building energy use. This is important because heating often uses natural gas which has a different cost than electricity. The natural gas and electrical utility rates can be multiplied by the annual energy consumption to provide an annual cost. This lets the simulation output provide the annual energy sustainment cost. The annual sustainment costs can be added to acquisition costs, or the cost of construction, for the total cost. When the construction materials are varied, the total life-cycle costs may be compared.

OpenStudio was used in a pilot study simulation to ensure proper application to this research. Using a template building, the following were the energy outputs: (1) 186.78 GJ of total annual energy, (2) 76.08 GJ of annual natural gas energy, and (3) 110.70 GJ of annual electrical energy. The U.S. Energy Information Administration (U.S. EIA) provides reputable energy information on utility rates and projection estimates for future rates [49]. For example, using the U.S. EIA database, the electrical energy cost for the East North Central can be estimated to be 10.28 cents per kilowatt hour (kWh) in 2020. Multiplying this value with the annual electrical energy for the building and the conversion factor for GJ to KWh provides an annual electrical energy bill of $3,161.10. This value is reasonable given the small facility modeled with the pilot study. The facility is comparable in size to a larger residential building but used for commercial purposes. The actual prototypical facilities used for the research differ greatly in shape and size than the pilot study building; however, the pilot study demonstration provided value in becoming familiar with the BPS software, ensured the BPS software was suitable for the research, and further developed the simulation methodology.

The EnergyPlus BPS successfully demonstrated the ability to model the annual building energy use and successfully showed that it is appropriate for this research. OpenStudio and EnergyPlus provided an effective platform to perform the simulation and modeling. However, their limitations and constraints should not be ignored. A negligible difference in the life-cycle analysis was assumed for the maintenance and repair costs for different construction materials. The simulation selection was constrained with the requirement to ensure the process was repeatable, which occasionally sacrificed complexity and accuracy for an easier simulation to learn and document. The simulation settings were limited from not including extensive HVAC analysis for internal loading to include zoning, HVAC sizing, or variations in HVAC type. The prototypical buildings used in this research were also constrained to the cost parameters that allow them to be built within the Air Force minor construction program. Not only did OpenStudio prove to be suitable for this research, it also enables countless additional research opportunities for alternative construction materials. Furthermore, each construction parameter can be considered for study and analysis in order to identify more cost effective and energy efficient construction methods or standards.

Part III: Input Variables and Simulations

The three key building parameters for this study are the building location, building size, and insulation standard. The building locations were chosen to represent cold, mild, and hot climates and are located within zones 2A, 3B, 4A, 5A, 6A, and 7A based on the ASHRAE climate zone map presented in Figure 1. The cold climates were Minot Air Force Base in Minot, North Dakota and Ellsworth Air Force Base near Rapid City, South Dakota; the mild climates were Wright Patterson Air Force Base in Dayton, Ohio and Langley Air Force Base in Newport News, Virginia; and the hot climates were Edwards Air Force Base near Bakersfield, California and JB San Antonio in San Antonio, Texas. The weather data was downloaded at https://www.energyplus.net/weather where EnergyPlus has combined over 20 different reputable weather data sources, as described in Part II. Again, this research used 'typical meteorological year 3' weather data which is derived from the NSRDB archives. The NREL manages these data files by ensuring their accuracy and improving the data quality. This model did not focus on humidity outside of the local weather patterns since this would introduce another key building parameter. This was the justification for choosing most bases within the ASHRAE 'A' zones which represent moist climate locations relative to the United States.

The next key building parameter is the building size. The size, shape, and orientation of the building all influence how heat flows through the building. These factors affect how solar and wind interacts with the building, which impacts the heat loss or gain. Air Force buildings are constructed in many various sizes and shapes depending on the land available, the function or mission of the facility, and pre-existing buildings. Therefore, both a smaller and larger facility were used in this simulation to determine how the size affected the construction standards.

Rather than designing and creating a prototypical building, previous research was used to ensure credibility in the model, prevent recreating research effort, and ensure consistency in the study. The Pacific Northwest National Laboratory (PNNL) was contracted by the Department of Energy to create and build models of prototypical government office buildings to be used for additional research efforts [50]. Two of these buildings were selected for use in this research. Using these prototypical buildings as a common starting point allows for better sharing and comparing of research results to more quickly progress towards energy efficient building practices. The function of these buildings aligned with the goal for office space and government employee occupants. The buildings' purposes match exactly with the simulation intent. The smaller building is a 5,506 square foot, single story facility with typical two-by-four framed walls used as an office building. Figure 2 shows a visual representation of the smaller building shape and size.

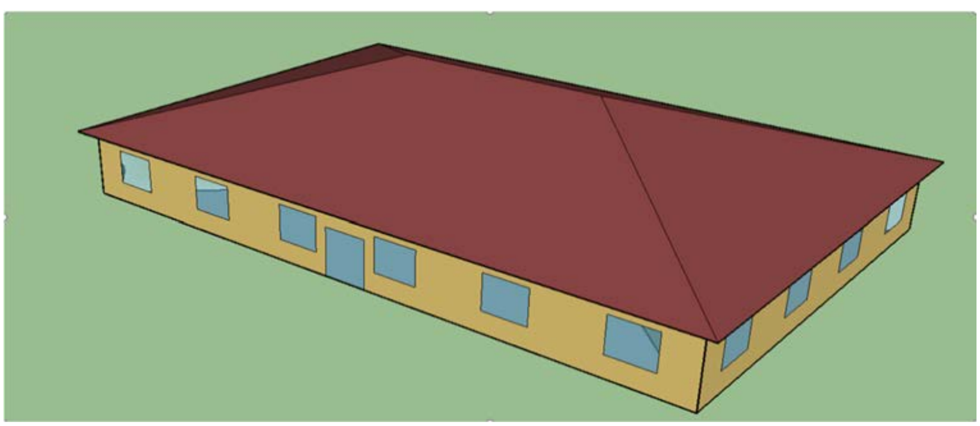


Figure 2: 5,506 square feet prototypical office space building developed by the Pacific Northwest National Laboratory

The larger building is a 20,000 square foot, three story facility with typical two-by-four steel frame construction walls using lightweight concrete for the floors. The building design and construction layout was not modified, except for the key building parameters used in the comparisons and the internal loads which were adjusted to reflect Air Force office use and schedule. Figure 3 shows a visual representation of the larger building shape and size.

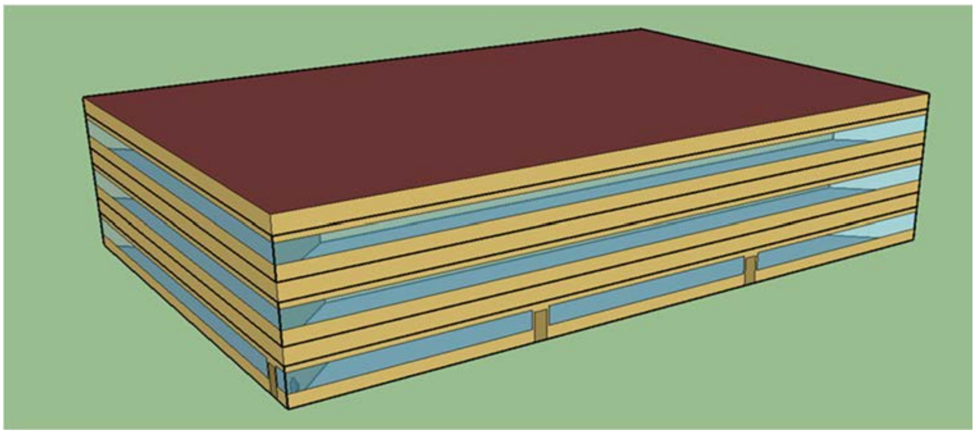


Figure 3: 20,000 square feet prototypical office space building developed by the Pacific Northwest National Laboratory

The largest modification to the prototypical office space buildings occurred in OpenStudio's section two, named schedules. This section defines the occupants within the building, the heat generated by a typical occupant, the operating equipment, the lighting, the water system, and the values and schedules that the HVAC system operates. These values were set to follow typical Air Force operations which involved a standard 07:30 to 16:30 workday with some personnel arriving earlier and several working late. It included a decrease in operations around a lunch hour and no one working on the weekend. However, the facility maintained a minimum operational level to include emergency lighting, a baseline HVAC temperature, and powered equipment while plugged in. Although the smaller and larger building had some differences based on the sizes of the facilities, such as the HVAC system servicing the facility, the profiles were kept as consistent as possible between the two facilities. These profile default settings and selected values can be viewed in more detail in Appendix A and Appendix B.

One more default value that did not reflect typical Air Force office space was the people per space floor area located in OpenStudio's fourth section, named loads. This value was modified to be 0.06 people per square meter in both facilities to be consistent. This equates to approximately 180 square feet per person working in the facility. Standard rule of thumb design practices uses an average of 125 to 150 square feet of office space per person. However, this does not account for unusable space such as corridors, bathrooms, etc. Therefore, 180 square feet was used to account for these additional spaces throughout the facilities.

The last key building parameter varied in the OpenStudio simulation was the insulation material used in the walls and roof. The R-value is how insulation standards are discussed and reported in the United States. This is a measure of a material's thermal resistance using the English or Imperial measurement system. The R-Value System International (RSI) is the International System (SI) conversion for thermal resistance. The thermal conductivity refers to the inverse of the thermal resistance which is also known as the U-Value in the English system. Both thermal resistance and thermal conductivity are based on the thickness of the material and the type of material. Doubling the thickness will double the thermal resistance. To compare materials without considering the thicknesses, thermal conductivity is often reported using the conductivity per meter nomenclature.

Table 2 shows the values used for each of the insulation standards throughout this research. The two prototypical office building models used different input variables for the insulation material properties in the OpenStudio's third section, named constructions. The small facility used the RSI value for the insulation while the large facility used the conductivity per meter metric. The two inputs represent the same values, but the two prototypical models used different input metrics for thermal properties of materials required these unit conversions. The two input metrics combined with the confusingly similar thermodynamics nomenclature were the reason for clearly presenting all these values in Table 2.

Table 2: Conversion of insulation values used as input parameters in OpenStudio

Insulation	Thermal Resistance (R-Value)	Thermal Resistance (RSI)	Thermal Conductivity	Thickness	Conductivity per meter
Wall	11	1.937	0.516	0.089	0.0459
	13	2.290	0.437	0.089	0.0388
	15	2.642	0.379	0.089	0.0337
	21	3.698	0.270	0.089	0.0240
Roof	30	5.284	0.189	1.000	0.1893
	38	6.692	0.149	1.000	0.1494
	49	8.630	0.116	1.000	0.1159
	60	10.567	0.095	1.000	0.0946
Units	$\frac{ft^2 * °F * h}{BTU}$	$\frac{m^2 * °K}{W}$	$\frac{W}{m^2 * °K}$	m	$\frac{W}{m * °K}$

Many different organizations develop construction codes for governments or organizations to adopt as either mandatory requirements or voluntary standards. The construction code requirements depend upon the regulatory laws of the country, state, and local municipality where the construction is occurring. Insulation construction standards in the United States are primarily specified from the state governments. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) is one organization that published a construction standard named ASHRAE Standard 90.1 that has been widely adopted in the construction industry. Some other standards used frequently in the United States include the International Building Code (IBC), the International Residential Code (IRC), the International Energy Conservation Code (IECC), and state developed construction codes. New revisions of these codes are published every few years which can significantly change the required insulation requirements. For example, the 2007 ASHRAE

Standard 90.1 requires R-38 insulation in attic roofing for ASHRAE climate zone 7, while the 2016 Standard 90.1 requires R-60 insulation. It is therefore important to know both the construction code standard and the published year required for a location.

Each of the six states used in this research have adopted different construction codes. The North Dakota Century Code Chapter 54 Section 21.3 makes amendments to the 2012 IRC, the 2012 IBC, and the 2009 IECC which are codified in the North Dakota Department of Commerce State Building Code [51], [52]. The South Dakota Codified Laws Title 11 Chapter 10-5 requires compliance with the 2009 IBC and provides voluntary guidance to use the 2009 IECC [53]. The South Dakota state legislature provides latitude to its local municipalities to determine the specifics of their own construction codes. Ohio Administrative Code Chapter 4101:1-13 requires compliance with the 2010 ASHRAE 90.1 Standard [54]. The Virginia Construction Code 1301.1.1.9-10 specifies its own state developed construction standard [55]. The California Code of Regulation Title 24 Part 6 Subchapter 2 Section 110.8 and Subchapter 7 Section 150.0 also specify its own state developed construction standards [56], [57]. The California legislature has divided the state into 16 different climate zones which are used in its code regulations, similar to the ASHRAE climate zones. The Texas State Code Title 7 Section 214.216 and Title 5 Section 388.003 require compliance with the 2015 IECC. This research used the 2010 ASHRAE 90.1 Standard as the construction code that requires R-13 insulation in the two-by-four wall cavity and R-38 insulation in the attic roof for ASHRAE zones one through six. This provided a consistent construction code standard for all six locations for the analysis. Additionally, this construction code met or exceeded the construction code for each of the six states considered for the building types used in this research.

The insulation values chosen as input parameters were selected to represent commercially and easily obtainable materials that are commonly used in construction. Additionally, they represent one value that is below code, one at code, one that exceeds the minimum code, and one that greatly exceeds the minimum code for both the wall and roof. For each building size at each of the six locations, every combination of these wall and roof insulation standards were simulated. This created 16 different simulations for each of the six configurations of size and location for a total of 192 separate simulations. Once OpenStudio successfully ran the simulations and provided the results reports, the energy annual energy consumption values were recorded. The annual energy consumption could then be used to perform a life-cycle analysis and economic comparative analysis which is further detailed in Chapter 4.

Chapter Summary

This chapter (a) outlined the methodology to selecting the appropriate BPS software for this specific research effort, (b) described the OpenStudio settings and inputs, (c) described the pilot study to demonstrate the BPS capabilities and advantages, and (d) presented the input variables and settings used for the prototypical Air Force office building insulation simulations. The results and interpretations of the research findings are discussed in Chapter 4.

CHAPTER 4: RESULTS AND ANALYSIS

Chapter Overview

This chapter presents the results from this research and includes the BPS software output, the life-cycle analysis, and the economic analysis. This chapter is organized into three separate parts. In Part I, the energy performance results from EnergyPlus and OpenStudio are presented. In Part II, the life-cycle cost analysis (LCCA) is applied to the simulation output. Finally, in Part III, the economic analysis compares construction alternatives to determine the best value parameters.

Part I: Building Performance Simulation (BPS) Output

The OpenStudio BPS software performs the simulation algorithm in section 14 based on all the parameters and settings input throughout sections 1-13. The software must initialize the workflow, process the OpenStudio measures from the inputs, translate the OpenStudio model to EnergyPlus, apply the inputs to the EnergyPlus model, perform the iterative simulation, and finally present the results in the reports found in section 15. The reports can provide a multitude of analytical information for the building such as total energy flow, orientation impact, zoning performance, air flow, equipment energy use, water use, HVAC efficiencies, and many more. For this research, the focus of the results reported is the total energy flow which provides information on the energy loss through the building envelope and the annual energy cost.

The first relevant OpenStudio report is the ‘site and source energy table’ found in section 15. The site energy is the total of all energy required to operate the facility throughout the year based on the OpenStudio model. This includes the energy required for all HVAC operations, internal equipment operations such as lighting, outlet loads, and building system operations. It provides a single summary value for the annual energy required, but it does not provide a breakdown of what is using the energy or what kind of energy is required. Table 3 provides an example of the 'site and source energy table' for the small facility located at Wright Patterson AFB with R-11 wall insulation and R-30 roof insulation.

Table 3: Example of an OpenStudio report on Site and Source Energy

	Total Energy [GJ]	Energy Per Total Building Area [MJ/m2]	Energy Per Conditioned Building Area [MJ/m2]
Total Site Energy	244.46	478.25	478.25
Net Site Energy	244.46	478.25	478.25
Total Source Energy	753.21	1473.55	1473.55
Net Source Energy	753.21	1473.55	1473.55

The source energy provides a holistic view of the total energy required to power the facility. It not only includes the total energy required from the facility but also includes the transmission, delivery, and production energy losses required for the facility to operate. For example, energy losses are experienced when producing energy into a form that can be distributed from an energy plant to the building location. Additionally, the energy distribution infrastructure also experiences energy losses while transporting the energy over distance. The source energy includes the energy lost in these processes to provide the site energy required for the facility. The source energy can be influenced by the type of energy the building systems utilize. For example, an on-site natural gas boiler and a centralized steam plant can provide the exact same site energy for building heating but would provide different source energy values. The focus of this research was the building envelop and not the HVAC system selection, so site energy was used in the analysis rather than the source energy.

The 'site and source energy table' provides valuable information on the magnitude of the energy required for the facility, but it does not provide specifics necessary for a cost analysis. The 'site energy subcategory end use table' provides a further breakdown of the building energy to include the type of energy and the system or category of energy use. Table 4 shows an example of the 'site energy subcategory end use table' for the small facility located at Wright Patterson AFB with R-11 wall insulation and R-30 roof insulation.

Table 4: Example of an OpenStudio report on Site Energy Subcategory End Use

	Electricity [GJ]	Natural Gas [GJ]	Additional Fuel [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	16.99	10.08	0.00	0.00	0.00	0.00
Cooling	17.96	0.00	0.00	0.00	0.00	0.00
Interior Lighting	73.99	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	25.66	0.00	0.00	0.00	0.00	0.00
Interior Equipment	58.98	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	22.80	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	18.01	0.00	0.00	0.00	0.00	30.12
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	234.38	10.08	0.00	0.00	0.00	30.12

It is important to be able to separate the energy use into electricity and natural gas since they have different costs. It is beneficial to see the energy categories during the simulation iterations to identify which categories change with the key building input parameters. The fans, heating, and cooling category values change when varying the insulation used in the facilities. The lighting, equipment, and building systems use a baseline energy cost which did not fluctuate with changing insulation values. Instead, these energy costs are the energy required to operate the facility based on the prototypical office building model and schedules selected. However, the most important values from this table for the cost analysis are the 'total end uses' value for the electricity and natural gas energy types. The electricity and natural gas 'total end uses' values can then be used for the economic analysis of each simulation configuration.

As mentioned in Chapter 3 within the 'pilot study simulation results' section, the U.S. Energy Information Administration (U.S. EIA) provides reputable energy information on utility rates and the best projection estimate for future rates [49]. The U.S. EIA database was used to estimate the electrical energy cost and natural gas energy cost for each location used in this research. The EIA utility rates used in this research were the annual estimate for 2020 and the data was taken from their open source website in October of 2019. Minot AFB and Ellsworth AFB are within the West North Central U.S. region, Wright Patterson AFB is within the East North Central U.S. region, Langley AFB is within the South Atlantic U.S. region, Edwards is within the Pacific U.S. region, and JB San Antonio is within the West South Central U.S. region. Table 5 presents the total energy required for each simulation configuration with different insulation values for the small prototypical office building at Wright Patterson AFB. It also includes the EIA utility rates used for the cost analysis and the annual electricity and natural gas costs to operate this facility. Appendix C provides the complete table for all simulations in addition to the one example presented in Table 5.

Table 5: Annual energy cost for small prototypical facility at Wright Patterson with different insulation values

WPAFB, OH		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	244.46	234.38	10.08	10.26	6.77	$ 6,967.11	$ 646.78
Insulation 2	Wall: R-13 Roof: R-30	243.09	233.52	9.57	10.26	6.77	$ 6,928.07	$ 614.05
Insulation 3	Wall: R-15 Roof: R-30	242.07	232.86	9.21	10.26	6.77	$ 6,899.00	$ 590.96
Insulation 4	Wall: R-21 Roof: R-30	240.15	231.64	8.51	10.26	6.77	$ 6,844.28	$ 546.04
Insulation 5	Wall: R-11 Roof: R-38	242.66	233.27	9.39	10.26	6.77	$ 6,915.81	$ 602.50
Insulation 6	Wall: R-13 Roof: R-38	241.29	232.41	8.88	10.26	6.77	$ 6,876.77	$ 569.78
Insulation 7	Wall: R-15 Roof: R-38	240.33	231.8	8.53	10.26	6.77	$ 6,849.41	$ 547.32
Insulation 8	Wall: R-21 Roof: R-38	238.58	230.65	7.93	10.26	6.77	$ 6,799.53	$ 508.82
Insulation 9	Wall: R-11 Roof: R-49	241.04	232.28	8.76	10.26	6.77	$ 6,869.64	$ 562.08
Insulation 10	Wall: R-13 Roof: R-49	239.83	231.5	8.33	10.26	6.77	$ 6,835.16	$ 534.49
Insulation 11	Wall: R-15 Roof: R-49	238.9	230.91	7.99	10.26	6.77	$ 6,808.65	$ 512.67
Insulation 12	Wall: R-21 Roof: R-49	237.31	229.83	7.48	10.26	6.77	$ 6,763.34	$ 479.95
Insulation 13	Wall: R-11 Roof: R-60	240.06	231.68	8.38	10.26	6.77	$ 6,841.71	$ 537.70
Insulation 14	Wall: R-13 Roof: R-60	238.92	230.93	7.99	10.26	6.77	$ 6,809.22	$ 512.67
Insulation 15	Wall: R-15 Roof: R-60	238.09	230.37	7.71	10.26	6.77	$ 6,785.57	$ 494.71
Insulation 16	Wall: R-21 Roof: R-60	236.46	229.28	7.18	10.26	6.77	$ 6,739.11	$ 460.70

Although utility rates fluctuate year to year, they tend to increase over time. For example, the East North Central commercial electricity rate has increased from 7.19 cents per kilowatt to 10.19 cents per kilowatt from 2000 to 2019. Since the rate that energy costs increase over time is difficult to reliably predict over time, the 2020 energy rate was used throughout the entire life-cycle analysis. This will conservatively calculate the energy savings since the actual cost savings will be greater depending on the increase in energy costs. Since this same assumption was applied to each configuration cost calculation, the error between comparisons is minimized. The same conservative calculation using the 2020 utility rates was applied consistently throughout this analysis.

Once the total energy and utility rates are known, the annual cost can be easily calculated. Multiplying the energy and rate together while using the appropriate unit conversions provides the annual cost for both electricity and natural gas. Summing these two energy costs together provides the total annual energy cost for sustaining the operations of this facility. The total annual energy cost is a recurring cost that must be paid each year. This annual energy cost is the final result from the simulation that will be used in the life-cycle and economic analysis to determine which insulation configuration is the better economic value.

In Part I, the process was presented to calculate the annual energy cost from the results of an OpenStudio simulation. The limitations and assumptions for the U.S. EIA utility rates used in the data analysis were discussed. An abbreviated table presenting the total energy and annual cost can be found in Table 5 and the full data table can be found in Appendix C. In Part II, the annual cost will be used in the life-cycle cost analysis to compare the results from different insulation configurations.

Part II: Life-Cycle Cost Analysis (LCCA) Results

A life-cycle analysis (LCA) is an analytical process to quantify the total costs of a system or component over its entire life span. It emphasizes the entire span of the system from initial production to decommissioning and disposal, which is commonly referred to as a cradle-to-grave scope [58]. The LCA is an appropriate evaluation tool for this data since the scope extends from the material acquisition cost at the procurement of the facility to the material replacement at the end of the construction material's life within the facility. The construction material should be used for the LCA scope instead of the entire facility since the building will continue to operate after the individual construction materials exceed their life. A renovation project can be performed to extend the useful operations of the facility based on asset management principles. However, to identify the most cost-effective construction standard for the insulation, only the construction material's life span needs to be considered for this LCA.

The three stages in the LCA process are inventory analysis, impact analysis, and improvement analysis [59]. The inventory analysis involves quantifying the system into its basic elements of raw materials, energy, wastes, and by-products. The simulation's inputs and the determination of the energy losses encompass the inventory analysis for this research. The material selections for each configuration in this study were also an important part of the inventory analysis which identified the raw material and costs for each configuration. The impact analysis stage is the technical analysis to quantify and assess the effects of the systems. For this research, the impact analysis is performed with the cost analysis that quantifies the life-cycle cost for each configuration over the life span of the insulation. Lastly, the improvement analysis is the study that systematically evaluates the opportunities to reduce the impact of the system. In this research, the improvement analysis is the economic analysis which compares the individual configurations to one another to determine the comparative benefits between the alternatives.

Many times, the focus of the LCA is placed on the impact analysis due to the technical assessment and decision-making emphasis, but each step in the LCA process is crucial for an accurate and meaningful result. A life-cycle cost assessment (LCCA) model is often used to analyze the system during the impact analysis phase. A LCCA is a systematic analytical process for evaluating various designs or alternative courses of actions with the objective of choosing the best way to employ scarce resources [59]. Many different models have been developed to apply LCCA to different situations and processes. All these models apply the LCA principles to reduce the total cost of a product, system, or asset, but they all apply these principles to different processes to emphasis differing priorities.

Durairaj et al. [59] provides a comparison of several preferred LCCA models to identify the differences and advantages of each. Table 6 summarizes the comparison to visually show the strengths and advantages of each model.

Table 6: A comparison of preferred LCCA models

No	Features	LCCA (Fab. & Bla.)	LCCA (Wood.)	LCCA (Dahlen)	ABC Model	EIO-LCA Model	DOC Model	PLCCA Model	TCA Model	LCECA Model
1	Objective	Cost Alternates	LCC of assets	LCC of labor	Cost Redn.	EIO analysis	Cost Evaln.	LCC estimates	TC calculation	Eco-design
2	Identification of alternatives	A	A	A	A	NA	A	NA	NA	A
3	Development of CBS & CBRs	E	E	E	E	G	G	G	A	E
4	Identification of suitable cost model	E	G	G	E	A	A	A	A	E
5	Generation of cost estimates	E	E	E	E	NA	A	NA	A	G
6	Availability of cost profiles	G	A	A	A	NA	A	NA	NA	G
7	Break Even Analysis	A	A	A	A	NA	NA	NA	NA	A
8	Determination of High Cost contributors	A	NA	NA	A	A	NA	NA	NA	A
9	Total Cost Determination	A	A	A	A	A	A	A	G	A
10	Incorporation of Eco-costs	NA	NA	NA	NA	NA	NA	A	NA	G
11	Correlation with Design changes	NA	NA	NA	A	NA	A	A	NA	A
12	Implementation of a Design solution	NA	NA	NA	A	NA	A	A	NA	A
13	Quality Aspects	NA	NA	NA	NA	NA	A	E	NA	NA
14	Inclusion of Supplier Relationships	NA	NA	NA	NA	E	NA	NA	A	A
15	Trade – offs	NA	E	NA	A	A	A	A	A	A
16	Employment cycles	NA	NA	E	NA	A	NA	NA	A	NA
17	Sensitivity Analysis	A	A	A	A	NA	NA	NA	NA	A
18	Risk Analysis	A	A	A	A	NA	A	A	NA	A
19	De-manufacture concept	NA	NA	NA	A	NA	A	A	NA	A
20	Any special feature	Holistic model	Asset model	Human factor	Uncertainty	Lca upgradn	Prod. sys.des.	Redesign	For projects	Eco-design

A, available; NA, not available; G, good; E, excellent.

Source: K. Durairaj, S. K. Ong, A. Y. C. Nee, and R. B. H. Tan, "Evaluation of life-cycle cost analysis methodologies," Corp. Environ. Strateg., vol. 9, no. 1, pp. 30–39, 2002

The LCCA model developed from Fabrycky and Blanchard [60] was selected for this research due to its objective being based in cost alternatives. The comparison between different construction materials in this study provides alternative construction options that need to be evaluated. Additionally, this LCCA model excels at focusing on the cost breakdown structure and cost estimating. Fabrycky and Blanchard's process involves problem definition, identification of alternatives, cost breakdown structure development, cost model selection, cost estimate development, analysis of results, and recommendations. The generic equation for a LCCA is [60]

$$\mathrm{LCC} = \mathrm{I} + \mathrm{E} + \mathrm{W} + \mathrm{OM\&R} + \mathrm{Repl} - \mathrm{Res} + \mathrm{O} \tag{6}$$

where

LCC is the total life-cycle cost in present value (PV) dollars of a given alternative, I is the initial cost to include development, acquisition, and construction costs,

E is the total energy costs,

W is the total water and other utility costs,

OM&R is the total operating, maintenance, and repair costs,

Repl is the capital replacement costs

Res is the residual value from resale or salvage after disposal costs at the end of life, and

O is all other costs, if any, such as administration, financing, human resources, etc.

Equation (6) provides the foundation for the LCCA for this research. However, it can be further simplified based on the study's scope and assumptions. Since the alternatives analyzed in this research are only the building insulations, many of these terms are zero or can be modeled as equivalent. The initial cost and energy costs are the primary terms that are considered in this research. The total water and other utilities for the facility are not impacted by the wall and roof insulation so they can be considered zero for this scope. The operating cost for building insulation is already quantified in the energy cost term, so it can also be considered zero. The maintenance and repair costs for the insulations are assumed to be equivalent for each alternative. Maintenance on insulation is rare since it typically is installed, ran to failure, and then replaced in whole. Repair of insulation is also rare when installed properly. The need for insulation repair will usually only be considered when another system fails and damages the insulation such as the roofing membrane or a water pipe. This should not be considered for this LCCA since it involves a corrective repair due to another system rather than preventative maintenance of the system being analyzed. The replacement value is also not considered in this analysis since the building would continue to operate at the end of the system life and require a replacement of the same system. The iterative asset replacement is cyclical so the replacement cost would be the acquisition cost of the next iteration. Each construction material being considered has the same life span and replacement timeline. Insulation does not have any residual value at the end of its life and must simply be disposed. Lastly, no other costs need to be considered for this analysis such as financing or administration. The equation after applying equation (6) to this study simplifies to

$$\mathrm{LCC} = \mathrm{I} + \mathrm{E} \tag{7}$$

where

LCC is the total life-cycle cost in present value (PV) dollars of a given alternative,

I is the initial cost to include acquisition and construction costs,

E is the total energy costs.

Fabrycky and Blanchard [59] model the cost breakdown structure using different language than the generic LCCA. Their cost breakdown structure uses four categories to identify costs: (1) research and development costs, (2) production and construction costs, (3) operation and maintenance costs, and (4) retirement and disposal costs. When applied to this study, the research and development costs and the retirement and disposal costs are zero. The production and construction costs are the same as the initial acquisition and construction costs. The operation and maintenance costs are the same as the total energy costs. This simplifies the cost breakdown structure model to equal the same as equation (7). When using this equation to determine cost-effectiveness, the only evaluation criteria is the lowest life-cycle cost. Non-monetary considerations were not quantified and included in the evaluation criteria or recommendation since they are often project-specific.

The energy costs were calculated using the BPS software, but the acquisition and construction costs must be calculated using a different method. Gordian is a company that compiles and provides construction cost data in a format called RSMeans [61]. Gordian offers access to their information database through their RSMeans construction cost books or software. This researched used the 2017 book for 'Building Construction Costs with RSMeans Data' to estimate the costs of the construction. The book presents unit pricing on materials which include acquisition, installation, labor, and any equipment required for constructing with that material. It also provides information on city cost indexes, overhead, production rates, and typical crew composition. The Air Force frequently uses RSMeans construction cost estimating in its construction programs.

Table 7 provides an example of how the RSMeans data was used to calculate the acquisition cost for one insulation configuration at Wright Patterson AFB. RSMeans cost data is organized into divisions for similar types of work or disciplines. The insulation line items needed for this study are in division 07, thermal and moisture protection. RSMeans presents costs as unit pricing to allow calculations for different quantities. The quantity take-off measurements for these calculations were based on the prototypical building geometries. The small facility has 5,506 square feet of roofing and 2,388 square feet of exterior wall while the large facility has 5,000 square feet of roof and 8,040 square feet of exterior wall.

Table 7: Example of acquisition cost calculations for Wright Patterson AFB

Division 07: Thermal and Moisture Protection — Key: RS Means Data | Calculation | Adjustment Factor From City Cost Table

ID	Activity	Quantity	Unit	Daily Output	Duration (days)	Material ($/Unit)	Material Adj.	Material Cost	Crew	Labor ($/Unit)	Labor Adj. Factor	Labor Cost	Equip ($/Unit)	Equip Adj. Factor	Equip Cost	Total Cost	RSMeans Item Number
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000.0	SF	600	8.33	0.52	1.199	$ 3,117	1 Carp	0.66	1.127	$ 3,719	0	0.787	$ -	$ 6,836	07-21-16-10-2150
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"" thick, R30	5,000.0	SF	500	10.00	0.75	1.199	$ 4,495	1 Carp	0.79	1.127	$ 4,452	0	0.787	$ -	$ 8,947	07-21-16-10-2210
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000.0	SF	475	10.53	1.08	1.199	$ 6,473	1 Carp	0.83	1.127	$ 4,677	0	0.787	$ -	$ 11,150	07-21-16-10-2220
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"" thick, R30	5,000.0	SF	450	11.11	0.62	1.199	$ 3,716	1 Carp	0.88	1.127	$ 4,959	0	0.787	$ -	$ 8,675	07-21-16-10-3020
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040.0	SF	1350	5.96	0.32	1.199	$ 3,084	1 Carp	0.29	1.127	$ 2,628	0	0.787	$ -	$ 5,712	07-21-16-20-0020
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040.0	SF	1350	5.96	0.48	1.199	$ 4,626	1 Carp	0.29	1.127	$ 2,628	0	0.787	$ -	$ 7,254	07-21-16-20-0420
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040.0	SF	1350	5.96	0.5	1.199	$ 4,819	1 Carp	0.29	1.127	$ 2,628	0	0.787	$ -	$ 7,447	07-21-16-20-0444
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040.0	SF	1715	4.69	1.81	1.199	$ 17,444	G-2A	0.53	1.214	$ 5,173	0.39	0.787	$ 2,468	$ 25,085	07-21-29-10-0335
																$ 14,659	
														Overhead	10%	$ 1,466	
														Profit and Contingency	5%	$ 806	
														Total		$ 16,930.69	

Once the quantity and unit cost are known, the cost must be adjusted based on the city cost factors for the construction's location. The material, labor, and equipment price vary based on the economics and markets of the city where construction occurs. Table 8 provides more details on the city cost index calculations. The labor adjustment factor requires additional details on the trades of the personnel performing the work, which is all available within the RSMeans building construction book. Different construction trades have different overhead costs that are affected by their hourly wage and expertise. Once the city indexes are known, the total cost for a line item can be calculated. Then the line items that are applicable for each specific insulation configuration are selected and summed for a total configuration cost. Lastly, the cost must be adjusted to include inflation, overhead, profit, and contingency. Once adjusted, the total acquisition cost for the insulation configuration has been calculated. Appendix D provides all the tables and calculations for each location.

Table 8: City cost index with labor overhead and labor adjustment factor calculations for Wright Patterson AFB

City Cost Table (Dayton, OH p.787)

Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	1.062	1.199	1.432	0.787	1.127	0.787
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	1.062	1.199	1.543	0.787	1.214	0.787

Labor Overhead and Labor Adjustment Factor Table

Crew		hour	daily	# Workers	B (From Table in Back Cover of RSMeans)	C	D	B + C + D	Workers x rate	Total Crew Rate	work rate	Total Labor OH	Labor Overhead Total Labor OH / Total Crew Rate
G-2A	1 Roofer Composition	43.15	345.2	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.1	256.8	1	30.7	18.3	11	60	32.10		19.26		
	1 Building Laborer	39.15	313.2	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		62.06	0.543
1 Carp	1 Carpenter	49.25	394	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		21.28	0.432

Table 9 provides a summary of the total acquisition costs and annual costs calculated for each insulation configuration, location, and building size. These two values enable the life-cycle cost to be calculated using equation (7). The economic analysis for comparing the different configurations to determine the most cost effective can also be calculated with these values. The economic analysis will be discussed further in Part III.

Table 9: Acquisition and annual costs for each simulation configuration

	Small Facility						Large Facility					
	Minot AFB		Ellsworth AFB		WPAFB Small Facility		Minot AFB		Ellsworth AFB		WPAFB	
Insulation Configuration	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost
1	$13,951.64	$11,199.77	$10,997.00	$ 9,395.13	$13,337.92	$ 7,613.89	$17,702.10	$37,997.65	$14,005.05	$34,890.69	$16,930.69	$31,276.19
2	$14,492.15	$11,022.54	$11,510.60	$ 9,254.52	$13,866.97	$ 7,542.12	$19,521.74	$37,742.12	$15,734.13	$34,667.20	$18,711.76	$31,114.88
3	$14,559.71	$10,882.32	$11,574.80	$ 9,141.13	$13,933.10	$ 7,489.95	$19,749.19	$37,543.02	$15,950.26	$34,492.78	$18,934.39	$30,989.76
4	$20,827.32	$10,601.54	$16,938.16	$ 8,939.07	$19,984.52	$ 7,390.32	$40,849.43	$37,142.85	$34,006.29	$34,143.37	$39,306.82	$30,736.97
5	$16,828.61	$10,953.45	$13,632.06	$ 9,194.55	$16,140.02	$ 7,518.31	$20,314.91	$37,572.80	$16,398.17	$34,516.89	$19,475.51	$31,004.87
6	$17,369.12	$10,770.31	$14,145.67	$ 9,061.83	$16,669.07	$ 7,446.55	$22,134.55	$37,318.40	$18,127.25	$34,294.26	$21,256.58	$30,844.13
7	$17,436.68	$10,632.66	$14,209.87	$ 8,960.31	$16,735.20	$ 7,396.73	$22,362.01	$37,119.02	$18,343.38	$34,120.69	$21,479.21	$30,719.58
8	$23,704.29	$10,339.30	$19,573.22	$ 8,767.55	$22,786.62	$ 7,308.35	$43,462.25	$36,720.83	$36,399.40	$33,773.26	$41,851.64	$30,468.50
9	$22,746.01	$10,726.46	$17,502.61	$ 9,027.01	$21,685.46	$ 7,431.72	$25,688.99	$37,207.79	$19,913.33	$34,196.98	$24,511.79	$30,774.87
10	$23,286.52	$10,541.69	$18,016.21	$ 8,900.55	$22,214.51	$ 7,369.65	$27,508.63	$36,953.96	$21,642.41	$33,975.76	$26,292.85	$30,615.56
11	$23,354.08	$10,388.89	$18,080.41	$ 8,803.50	$22,280.64	$ 7,321.32	$27,736.09	$36,755.72	$21,858.55	$33,802.76	$26,515.49	$30,491.58
12	$29,621.69	$10,115.72	$23,443.77	$ 8,615.65	$28,332.07	$ 7,243.29	$48,836.33	$36,358.94	$39,914.57	$33,457.32	$46,887.92	$30,241.92
13	$25,535.09	$10,574.23	$19,832.01	$ 8,923.21	$24,370.28	$ 7,379.41	$28,221.98	$36,977.22	$22,028.86	$33,996.18	$26,950.09	$30,632.09
14	$26,075.59	$10,383.84	$20,345.62	$ 8,798.80	$24,899.32	$ 7,321.89	$30,041.62	$36,723.95	$23,757.94	$33,775.25	$28,731.15	$30,473.06
15	$26,143.15	$10,234.74	$20,409.82	$ 8,703.10	$24,965.45	$ 7,280.27	$30,269.08	$36,526.56	$23,974.07	$33,603.10	$28,953.79	$30,349.65
16	$32,410.76	$ 9,971.38	$25,773.18	$ 8,525.56	$31,016.88	$ 7,199.81	$51,369.31	$36,130.64	$42,030.10	$33,257.94	$49,326.22	$30,101.13
Average	$21,771.40	$10,583.68	$17,249.06	$ 8,938.22	$20,826.13	$ 7,390.85	$29,735.51	$37,049.47	$24,005.24	$34,060.28	$28,507.24	$30,677.17

	Small Facility						Large Facility					
	Langley AFB Small Facility		Edwards AFB		JB San Antonio		Langley AFB		Edwards AFB		JB San Antonio	
Insulation Configuration	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost	Acquisition Cost	Annual Cost
1	$12,369.08	$ 7,887.26	$16,994.26	$ 9,169.51	$11,867.06	$ 5,334.47	$15,720.10	$33,235.54	$21,470.39	$35,453.21	$15,071.04	$21,521.54
2	$12,892.15	$ 7,856.41	$17,496.90	$ 9,146.98	$12,350.28	$ 5,321.66	$17,481.04	$33,107.93	$23,162.57	$35,343.17	$16,697.82	$21,477.28
3	$12,957.53	$ 7,836.81	$17,559.73	$ 9,130.38	$12,410.68	$ 5,312.33	$17,701.16	$33,008.93	$23,374.09	$35,258.46	$16,901.16	$21,442.36
4	$18,726.18	$ 7,791.63	$24,441.75	$ 9,097.95	$17,855.22	$ 5,293.20	$37,121.62	$32,809.96	$46,542.76	$35,092.21	$35,230.49	$21,373.58
5	$15,103.78	$ 7,845.15	$19,845.29	$ 9,146.98	$14,412.64	$ 5,320.14	$18,203.71	$33,018.14	$24,059.65	$35,277.85	$17,382.89	$21,445.18
6	$15,626.85	$ 7,817.68	$20,347.93	$ 9,124.85	$14,895.85	$ 5,307.54	$19,964.65	$32,891.52	$25,751.83	$35,170.58	$19,009.67	$21,401.35
7	$15,692.23	$ 7,795.36	$20,410.76	$ 9,108.24	$14,956.26	$ 5,297.76	$20,184.77	$32,793.18	$25,963.35	$35,088.25	$19,213.01	$21,366.21
8	$21,460.88	$ 7,753.23	$27,292.78	$ 9,076.22	$20,400.80	$ 5,279.08	$39,605.23	$32,597.16	$49,132.02	$34,925.96	$37,542.34	$21,298.52
9	$19,952.28	$ 7,813.31	$28,464.72	$ 9,127.62	$19,233.15	$ 5,307.54	$22,607.03	$32,837.25	$31,887.67	$35,148.42	$21,760.80	$21,384.21
10	$20,475.35	$ 7,785.84	$28,967.37	$ 9,106.26	$19,716.37	$ 5,294.94	$24,367.98	$32,711.62	$33,579.85	$35,043.13	$23,387.58	$21,340.61
11	$20,540.74	$ 7,760.25	$29,030.20	$ 9,089.66	$19,776.77	$ 5,285.61	$24,588.09	$32,614.60	$33,791.37	$34,961.58	$23,590.92	$21,306.33
12	$26,309.39	$ 7,714.53	$35,912.22	$ 9,057.25	$25,221.31	$ 5,266.93	$44,008.55	$32,420.88	$56,960.05	$34,802.46	$41,920.25	$21,240.16
13	$22,490.62	$ 7,791.76	$31,629.06	$ 9,115.37	$21,640.61	$ 5,299.06	$24,912.31	$32,726.09	$34,761.47	$35,074.79	$23,947.21	$21,347.12
14	$23,013.69	$ 7,761.57	$32,131.71	$ 9,094.01	$22,123.83	$ 5,286.46	$26,673.25	$32,600.78	$36,453.65	$34,969.90	$25,573.99	$21,303.73
15	$23,079.08	$ 7,735.32	$32,194.54	$ 9,077.02	$22,184.23	$ 5,277.35	$26,893.37	$32,505.40	$36,665.17	$34,890.33	$25,777.33	$21,269.88
16	$28,847.73	$ 7,689.26	$39,076.56	$ 9,045.39	$27,628.77	$ 5,258.67	$46,313.83	$32,313.00	$59,833.85	$34,732.79	$44,106.66	$21,203.72
Average	$19,346.10	$ 7,789.71	$26,362.24	$ 9,107.11	$18,542.11	$ 5,296.42	$26,646.67	$32,762.00	$35,211.86	$35,077.07	$25,444.57	$21,357.61

Part III: Construction Engineering Economic Analysis Results

Simply calculating the total life-cycle cost and comparing the result may seem to be an appropriate analysis to determine the most cost-effective insulation configuration, but it would ignore important economic principles which must also be considered. The time-value of money is the economic concept that money available at a present time is worth more than the same amount of money at a future time. The potential to invest and earn money with present money makes it more valuable than the identical amount in the future. Interest, investment opportunity, and inflation all contribute to the time-value of money concept.

Since the analysis of the facility occurs over a 25-year period, the time-value of money concept must be included in the analysis. Each insulation configuration has a different investment principle and annual energy cost that must have the time-value of money applied individually. The formula for the present value of an annuity is

$$\mathrm{PV} = \mathrm{A} * \left(\frac{1-(1+r)^{-n}}{r}\right) \tag{8}$$

where

PV is the value in dollars at present time,

A is the annuity for each period in dollars,

r is rate per period, and

n is the number of periods.

Equation (8) determines the value for a series of equal, future periodic payments at a given present time. Quantifying the money accumulated or spent over periods of time can be modeled using a cash flow. This equation can be applied to this study's cash flow to determine the internal rate of return for each configuration. The internal rate of return is the percentage rate that would make the present value cost equal to the annual annuity present value. The acquisition cost is used for the present value cost, the annual energy cost is used for the annuity, and the number of periods is the 25-year life span of the insulation. The internal rate of return can be calculated by solving equation (8) for the rate per period.

The primary advantage of internal rate of return is that it is well-suited for analyzing mutually exclusive alternatives. When comparing one alternative to another, the internal rate of return is a consistent metric to evaluate performance. It incorporates the time value of money without dictating or estimating the interest, investment, or inflation rates. Instead, it presents a single rate and allows the decision maker to determine whether the project or investment is worthwhile based on the situation. A Minimum Attractive Rate of Return (MARR) is the minimum interest rate that an investment must earn to be attractive to an investor. For example, one business may see an investment with an internal rate of return of 9% as a worthwhile pursuit due to their other investment opportunities while another business may see it as a poor investment based on their MARR. Using the internal rate of return metric enables transparency in the analysis which avoids making invalid assumptions on the specific rates. Instead, the decision maker can compare their situation's rates to the internal rate of return in the results. This makes the research results appropriate for a wider base of applications.

Using internal rate of returns can be deceiving because it does not consider the magnitude of the cash flow values. Instead, the internal rate of return is a percentage that balances the equation over the time period. Additionally, it does not include associated future costs. For this application, an associated future cost not included could be the replacement renovation costs. This disadvantage of associated future costs is minimized for this application since the renovation would be required for each alternative. Another disadvantage of the internal rate of return is that it ignores reinvestment rates and instead assumes a constant rate throughout the life of the equation. In actuality, the inflation, investment opportunities, and interest rates all vary over time. However, these fluctuations are hard to predict, so they are modeled as a constant to allow for the cost analysis and comparison of alternatives.

The internal rate of return should only be used to compare two configurations to one another when used as an evaluation metric. This minimizes potential misinterpretation of the results due to the magnitudes of the cash flows. Three analyses were performed to show which configuration was the most cost effective. The first analysis simply compared the insulation configuration to the default of installing no insulation. The purpose of this analysis was to provide information for a baseline on the internal rate of return. Table 10 shows the rate of returns for each large building insulation configuration located at Wright-Patterson AFB. The highlighted row 6 refers to the insulation configuration that represents the minimum construction code. The insulation configurations were organized by increasing acquisition cost since the analysis is addressing mutually exclusive alternatives. This organization is particularly important for the third analysis performed.

Table 10: Internal rate of return for the large building insulations at Wright Patterson AFB compared to installing no insulation

Compared to Baseline (No Insulation)			WPAFB - Large Building		
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)
0	0	$ 40,007.73			
1	$ 16,930.69	$ 31,276.19	-16930.69	8731.54	51.57%
2	$ 18,711.76	$ 31,114.88	-18711.76	8892.86	47.52%
3	$ 18,934.39	$ 30,989.76	-18934.39	9017.97	47.62%
5	$ 19,475.51	$ 31,004.87	-19475.51	9002.86	46.22%
6	$ 21,256.58	$ 30,844.13	-21256.58	9163.61	43.10%
7	$ 21,479.21	$ 30,719.58	-21479.21	9288.15	43.24%
9	$ 24,511.79	$ 30,774.87	-24511.79	9232.86	37.65%
10	$ 26,292.85	$ 30,615.56	-26292.85	9392.18	35.70%
11	$ 26,515.49	$ 30,491.58	-26515.49	9516.15	35.87%
13	$ 26,950.09	$ 30,632.09	-26950.09	9375.65	34.77%
14	$ 28,731.15	$ 30,473.06	-28731.15	9534.67	33.16%
15	$ 28,953.79	$ 30,349.65	-28953.79	9658.08	33.33%
4	$ 39,306.82	$ 30,736.97	-39306.82	9270.77	23.46%
8	$ 41,851.64	$ 30,468.50	-41851.64	9539.24	22.65%
12	$ 46,887.92	$ 30,241.92	-46887.92	9765.81	20.64%
16	$ 49,326.22	$ 30,101.13	-49326.22	9906.60	19.87%

The initial inclination may be to interpret the results as insulation identifier 1 is the most cost effective with a rate of return of 51.57%. But this highlights the influence of the cash flow magnitudes on the internal rate of return. Because the rate of return is used as a comparative measure, it only accounts for the two values being compared. In this case, no insulation and the insulation configuration. It cannot be used as a measure to interpret two insulation configurations not used in the comparison to one another. This analysis only shows that each insulation configuration is more cost effective than installing no insulation when the MARR is less than 19.87%. However, the interpretation of this analysis does not answer the research questions since this study is not considering the case of no insulation.

The next analysis performed was to calculate the internal rate of return when comparing the insulation configurations to the construction code. However, the internal rate of return is nearly meaningless without the context of a MARR for a decision to be made from the comparison. Whether the internal rate of return is an attractive investment depends entirely upon the MARR. A 0% MARR would indicate that the business has no other investment opportunities and does not recognize the time value of money.

Table 11 presents the results of the second analysis performed on the large building located at Wright-Patterson AFB. The construction code, highlighted in orange, has an internal rate of return of 0% since it is being compared to itself. For ease of interpretation, the more cost-effective insulation configurations are highlighted in green using a MARR based on the interest rate on treasury notes and bonds. The government is not a business and uses taxpayer dollars to raise capital to operate. In order to determine a suitable MARR for application to the Air Force, the same interest rate and inflation assumptions used to prepare the Budget of the United States Government were used in this research. These assumptions and rates are published publicly and updated from the United States government's Office of Management and Budget (OMB) in a document named the Circular A-94 [62]. The interest rates on treasury notes and specified maturities should be used to estimate Air Force construction MARR. The 30-year rate is used due to its closeness to the 25-year analysis length of time. Since the inflation rate was not estimated and included in the utility rate calculations, the real interest rate should be used instead of the nominal rate. Using these criteria, the MARR used for this research application to Air Force construction was 0.4% [63].

Table 11: Rate of return for the large building insulations at Wright Patterson AFB compared to the insulation construction code, numbered 6

Compared to Standard			WPAFB - Large Building					Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 16,930.69	$ 31,276.19	4325.88	-432.06	8.77%	above	No	No	No
2	$ 18,711.76	$ 31,114.88	2544.82	-270.75	9.55%	above	No	No	No
3	$ 18,934.39	$ 30,989.76	2322.18	-145.63	3.81%	above	No	No	Yes
5	$ 19,475.51	$ 31,004.87	1781.07	-160.74	7.57%	above	No	No	No
6	$ 21,256.58	$ 30,844.13	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 21,479.21	$ 30,719.58	-222.63	124.54	55.94%	below	Yes	Yes	Yes
9	$ 24,511.79	$ 30,774.87	-3255.21	69.25	-4.36%	below	No	No	No
10	$ 26,292.85	$ 30,615.56	-5036.28	228.57	1.00%	below	Yes	Yes	No
11	$ 26,515.49	$ 30,491.58	-5258.91	352.54	4.44%	below	Yes	Yes	No
13	$ 26,950.09	$ 30,632.09	-5693.51	212.04	-0.54%	below	No	No	No
14	$ 28,731.15	$ 30,473.06	-7474.58	371.07	1.74%	below	Yes	Yes	No
15	$ 28,953.79	$ 30,349.65	-7697.21	494.47	4.03%	below	Yes	Yes	No
4	$ 39,306.82	$ 30,736.97	-18050.25	107.16	-11.30%	below	No	No	No
8	$ 41,851.64	$ 30,468.50	-20595.06	375.63	-5.31%	below	No	No	No
12	$ 46,887.92	$ 30,241.92	-25631.34	602.21	-3.73%	below	No	No	No
16	$ 49,326.22	$ 30,101.13	-28069.64	742.99	-2.95%	below	No	No	No

Since some comparisons have a lower initial cost than the construction code standard and some have a higher initial cost, the interpretation based on the MARR is not straightforward. The lower acquisition costs behave similar to a loan while the higher acquisition costs behave similar to an investment. A loan is enticing only if the MARR of another opportunity is above the interest rate on the loan, while an investment opportunity is enticing only if its rate of return is higher than the businesses MARR. To assist in interpreting the results, several MARRs are shown in Table 11. A column specifies whether the MARR should be above or below the insulation configuration's rate of return to be enticing. In addition to the 0.4% MARR used for this research, a 0% MARR and 6% MARR column was included just as additional examples.

These results show five insulation configurations that are more cost effective than the standard, which are numbered 7, 10, 11, 14, and 15. This information would be difficult to interpret from the first analysis. Again, care must be taken not to leap to the conclusion that configuration 7 is the most cost effective with the highest internal rate of return of 55.94%. This second analysis reveals that construction code is not the most cost-effective construction method for insulation using these key building parameters.

The third analysis performed using rate of return was to identify the best performer and investment opportunity for each insulation configuration. A process using internal rate of return comparisons was calculated called incremental analysis. Incremental analysis is an analysis method used to compare mutually exclusive alternatives to maximize benefit to the business. Incremental analysis orders the alternatives in increasing first cost order, compares each alternative to the current best investment starting at the top, and selects the alternative as the temporary best alternative if its benefit is better than the MARR [64]. Using internal rate of returns in the incremental analysis presents the single best value insulation configuration when evaluated at a specific MARR. Again, this analysis uses the 0.4% MARR provided in the OMB Circular A-94.

Table 12 presents the results of the third analysis performed on the large building located at Wright-Patterson AFB. Configuration 6 is highlighted in orange to represent the construction standard. 'N/A' represents an internal rate of return value that could not be calculated. When both the acquisition cost and the annual energy cost increase when compared to another insulation configuration, there is no interest rate that balances the cash flow. For example, no rate of return will cause configuration 8 to behave as a balanced cash flow since it costs more without providing any annual savings.

Table 12: Incremental analysis using internal rate of return for large building insulations at Wright Patterson AFB to identify the best performing configuration

Incremental Analysis			WPAFB - Large Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	0	$40,007.73					
1	$ 16,930.69	$31,276.19	-16930.69	8731.54	0	51.57%	Yes
2	$ 18,711.76	$31,114.88	-1781.07	161.31	1	7.61%	Yes
3	$ 18,934.39	$30,989.76	-222.63	125.12	2	56.20%	Yes
5	$ 19,475.51	$31,004.87	-541.12	-15.11	3	N/A	No
6	$ 21,256.58	$30,844.13	-2322.18	145.63	3	3.81%	Yes
7	$ 21,479.21	$30,719.58	-222.63	124.54	6	55.94%	Yes
9	$ 24,511.79	$30,774.87	-3032.58	-55.29	7	N/A	No
10	$ 26,292.85	$30,615.56	-4813.64	104.03	7	-4.27%	No
11	$ 26,515.49	$30,491.58	-5036.28	228.00	7	0.98%	Yes
13	$ 26,950.09	$30,632.09	-434.60	-140.50	11	N/A	No
14	$ 28,731.15	$30,473.06	-2215.67	18.52	11	-9.61%	No
15	**$ 28,953.79**	**$30,349.65**	**-2438.30**	**141.93**	**11**	**3.12%**	**Yes**
4	$ 39,306.82	$30,736.97	-10353.04	-387.31	15	N/A	No
8	$ 41,851.64	$30,468.50	-12897.85	-118.84	15	N/A	No
12	$ 46,887.92	$30,241.92	-17934.13	107.73	15	-11.24%	No
16	$ 49,326.22	$30,101.13	-20372.43	248.52	15	-7.61%	No

Configuration is bolded to call attention to its final selection as the best value for this incremental analysis. Configuration 15 represents an R-15 wall insulation which is above construction code and an R-60 roof insulation which is significantly above construction code. However, this result is only applicable for the key building parameters used with this data. It cannot be applied to all facilities without further research and support.

Table 13 presents the numerical data in Table 10, 11, and 12 in a visual table to allow for easier interpretation of the comparisons. The red shows a configuration that was less cost effective than the construction standard. The yellow indicates the construction standard. The green reveals the configurations that were more cost effective than the construction code standard. The asterisks point out the insulation configuration that was the most cost effective out of the 16 considered based on the incremental analysis. A 0.4% MARR was used.

Table 13: Summary of the comparative rate of returns for large building insulations at Wright Patterson AFB using the construction code as the baseline, shown in yellow

		WPAFB Large Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	7	11	***** 15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

A plot was developed using the acquisition and annual cost data to perform a verification analysis. The purpose of this analysis was to perform a quality control check on the calculated internal rate of return analysis. Additionally, the plot provided a quick visual to help identify high performing insulation configurations. Figure 4 shows the plot of insulation configurations of the large building located at Wright-Patterson AFB.

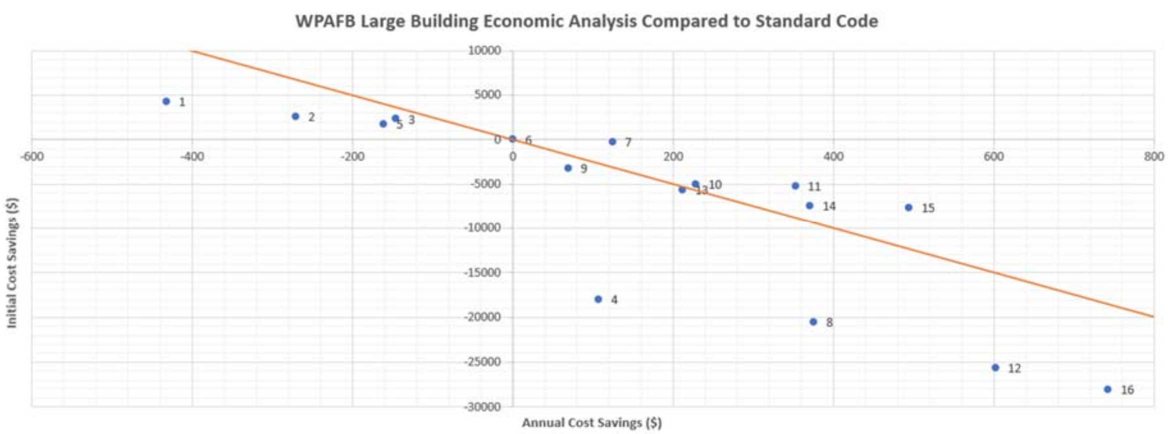


Figure 4: Scatter plot to identify the area of interest for high performing insulation configurations

The plot is centered using the construction standard as the origin, numbered 6. A linear interpretation line, shown in orange, was superimposed on the graph to assist in interpreting the graph. This line models values for similar performance to the construction standard using a MARR of 0%. It then allows for interpretation for an area of interest above the trend line as high-performing insulation configurations. Configurations 7, 10, 11, 14, and 15 all fall within this area of interest. The internal rate of return calculations and the plot both show that these were the insulation configurations that were better performing than the standard.

This graph provides valuable information on the magnitude of performance which can be difficult to determine using internal rate of return. For example, it shows that the best performer for this location and size, configuration 15, was the furthest above the trend line. This can also be calculated numerically from determining the data point above the trend line with the greatest perpendicular distance to the trend line. It also shows reveals configurations that are only barely outperformed by the construction standard, such as configuration 13 in this analysis. It also reveals that the closed-celled polyurethane spray (configurations 4, 8, 12, and 16) is significantly outperformed by the other configurations. This graph provides valuable validation of the internal rate of return results and adds important interpretation on the performance magnitudes.

The focus of results presented in part III was the large facility at Wright Patterson because its plot was uncluttered, easy to read, and clear to interpret. However, the analysis process was performed for each of the key building parameters used in the simulation. Each table and graph are not presented, but they can all be found in Appendix E and Appendix F. Table 14 summarizes the analysis for all the data considered in this study. It follows the same format and interpretation previously used.

Table 14: Summary of the comparative rate of return for all key building parameters using construction code as the baseline, numbered 6

		Minot Small Bldg				Minot Large Bldg			
Zone 7	ND	Below	Standard	Above	Sig Above	Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16	4	8	12	16
Above	R-15	3	7	11	***** 15	3	7	11	***** 15
Standard	R-13	2	6	10	14	2	6	10	14
Below	R-11	1	5	9	13	1	5	9	13
		Ellsworth Small Bldg				Ellsworth Large Bldg			
Zone 6	SD	Below	Standard	Above	Sig Above	Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16	4	8	12	16
Above	R-15	3	***** 7	11	15	3	7	11	***** 15
Standard	R-13	2	6	10	14	2	6	10	14
Below	R-11	1	5	9	13	1	5	9	13
		WPAFB Small Bldg				WPAFB Large Bldg			
Zone 5	OH	Below	Standard	Above	Sig Above	Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16	4	8	12	16
Above	R-15	***** 3	7	11	15	3	7	11	***** 15
Standard	R-13	2	6	10	14	2	6	10	14
Below	R-11	1	5	9	13	1	5	9	13
		Langley Small Bldg				Langley Large Bldg			
Zone 4	VA	Below	Standard	Above	Sig Above	Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16	4	8	12	16
Above	R-15	***** 3	7	11	15	3	7	11	***** 15
Standard	R-13	2	6	10	14	2	6	10	14
Below	R-11	1	5	9	13	1	5	9	13
		Edwards Small Bldg				Edwards Large Bldg			
Zone 3	CA	Below	Standard	Above	Sig Above	Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16	4	8	12	16
Above	R-15	***** 3	7	11	15	***** 3	7	11	15
Standard	R-13	2	6	10	14	2	6	10	14
Below	R-11	1	5	9	13	1	5	9	13
		San Antonio Small Bldg				San Antonio Large Bldg			
Zone 2	TX	Below	Standard	Above	Sig Above	Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16	4	8	12	16
Above	R-15	***** 3	7	11	15	***** 3	7	11	15
Standard	R-13	2	6	10	14	2	6	10	14
Below	R-11	1	5	9	13	1	5	9	13

The results show that the best performing insulation depends upon the key building parameters. Trends in the results can be found in performances based on the building sizes and the climates. In all cases, the best performing wall insulation was R-15 which is above the construction code. However, the best performing roof insulation changed depending on the key building parameters. The smaller facility showed R-30 which is below construction code as the best roof insulation in the hot and mild climates. The cold climate was split between the construction standard, R-38, and significantly above the construction standard, R-60. The larger facility showed R-60 which is significantly above the construction code as the best roof insulation in the cold and moderate climates. But in the hot climates, it showed that the R-30 was the best roof insulation. Additionally, the comparison tables within the cold, mild, and hot locations behaved very similarly. An inflection point can be identified in the small facility between climate zones five and six where the data shifts. Zones one through four all look almost identical while zones four and five look very different. The same inflection point can be identified in the large facility between zones three and four. Since the inflection point occurs in different locations for the two facility sizes, it indicates that the building size contributes to this relationship. The existance of the inflection points also reinforce that the climates, determined by the locations, have a direct and significant impact on the results.

The differences in the comparison tables between Edwards AFB in California and JB San Antonio in Texas were found to be caused by the utility costs. California had the largest utility cost of 14.25 cents per kW while Texas had the lowest utility cost of 7.81 cents per kW. All other locations were between 10 and 12 cents per kW. When Edwards was anayzed with the same rates as Texas, the comparison table was identical. This showed that the differences between these two locations were based on the utility markets rather than the weather or climate. Even with the economic markets between these states being so different, the comparison tables still show the similarities in the results due to the climates for these locations.

The results provide evidence to support that more cost effective construction can be built than just meeting the minimum construction code. This meets the primary objective of this research to provide a proof of concept on whether more cost efficient standards can be utilized than construction code. Therefore, the Air Force should not simply accept construction using LPTA acquisition contracts which simply build to the construction code without verification using heat flow analysis and calculations. The wall insulation provides a trend that deserves continued research and investigation to determine whether this improved standard should be consistently adopted in policy or process practices. The roof insulation appears to be more dependent on the size and location of the facility to determine the most cost effective insulation standard. The results reveal that no singular construction code will be the most cost effective in every location for every facility shape and size; instead, it is important to consider the specifics of the building being constructed to identify the best value construction standard.

Another factor that should be further considered is the effect of thermal bridging on the prototypical office building models. The window standards used in these models provide an opportunity to reduce the effects of thermal bridging and further improve the cost effectiveness of insulating the roof and walls. The large surface area covered by windows in these buildings causes increased diminishing returns when insulating the walls and roof. This could also be a key factor in the different trends seen in Edwards AFB and JB San Antonio where the cooling loads dominate the HVAC cycle. Expanding this research to include an analysis of window performance as a key building parameter could provide additional insight into the relationships between insulation and thermal energy efficiency.

Chapter Summary

The findings were presented from (a) the energy performance simulations with the key building parameter inputs, (b) the life-cycle analysis of the simulation outputs, and (c) the economic analysis comparing each mutually exclusive alternative. Despite the limitation of real-world data and the findings being confined to the boundaries established for the study, the results provide valuable insight into the best value construction standards. It establishes that construction code does not represent the most cost-effective insulation standard. Chapter 5 will expand on the research results presented in Chapter 4 and provide result impacts, assumptions, limitations, and final recommendations.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

Chapter Overview

This chapter provides final conclusions and recommendations from the research. First, a brief research summary is presented with the research questions from chapter 1. Second, the assumptions and limitations of the research are presented. Finally, the benefits and impacts of the research provide compelling suggestions for future research.

Research Summary

This research analyzed the potential energy performance benefits of different insulation standards for United States Air Force (USAF) office facilities using EnergyPlus and OpenStudio BPS software. The BPS software modeled the annual energy cost for each configuration. The acquisition costs were estimated using building construction costs with RSMeans data. This data enabled the economic viability to be determined using a life-cycle analysis for each model configuration. At each building location and size, the internal rate of return for each insulation standard were compared to the building code to determine which standards were economically viable and then which insulation standard was the best value for these parameters.

Research Questions Answered

1. *Will constructing to higher standards than the building code be more cost effective over a facility's life?*

Our results show that constructing to higher standards than the building code is usually more cost effective over a facility's life. These results only apply to the six locations selected for this research using the two prototypical office space buildings. The above code R-15 wall insulation was the most cost effective in all twelve location and building size scenarios modeled. This provided a clear consensus for the wall insulation that the building code should be exceeded for a more cost-effective alternative. However, the highest available insulation material, the closed-cell spray polyurethane foam, was not more cost effective than building code except at the cold climate locations. This material is newer technology with higher performance, but it also requires a high initial cost that was generally not an economically viable alternative.

Unlike the wall insulation, roof insulation did not have a consensus trend. The results show that the large facility located at cold and mild climates benefitted from exceeding the roof insulation construction code. Five scenarios showed that R-60 roof insulation was the best value from a life-cycle cost perspective. Only one scenario of the small facility in a cold climate showed that the standard R-38 roof insulation was the most cost effective. The other six scenarios all showed that the best value was constructing below the construction code for roof insulation. This research only used cost as a decision criterion and did not consider other considerations that are more difficult to quantify such as air quality, comfort, and humidity.

2. *Can an optimal insulation construction standard be developed for a prototypical Air Force office building?*

The results indicate that an optimal insulation construction standard could be developed. Although this study was limited to six locations and two sizes, future research could expand this scope to determine a wider reaching consensus for a construction standard. The results positively affirmed the proof of concept of the possibility for a more cost beneficial insulation standard than construction code. Since the roof insulation's best value standard depended upon geographic location, the construction standard could differ depending upon the ASHRAE climate zone. Additionally, the standard could also specify square footage ranges to account for the different building sizes. This would enable the best economic value across a wider range of locations and sizes. Further research could more accurately specify these specifics prior to adopting policy.

3. *Does building construction code specify the most cost-effective standards when analyzing a building's life-cycle energy efficiency?*

The results showed that building construction code was not the most cost effective in any of the twelve scenarios studied. Out of the sixteen combinations analyzed, the smaller facility had an average of 5.7 standard combinations that were more cost effective than the construction code. The larger facility had an average of five standard combinations that were more cost effective. This research provided evidence that there are cost savings opportunities in exceeding insulation construction code standards for the prototypical Air Force office space building.

4. *How can the Air Force receive the best value in facility construction from a life-cycle cost perspective with LPTA contracts?*

This research question was central to the development and execution of this thesis. The insulation standard is just one standard that was analyzed to find more economic alternatives. Rather than assuming the construction code is the most economic, the results provided evidence that the insulation standard used in construction should be analyzed and carefully selected. Some potential methods for recognizing these cost savings with the LPTA acquisition strategy include performing an energy flow analysis of the facility during the design phase of a project to identify the best life-cycle cost, specifying specific insulation standards in the contracting requirements, or implementing Air Force policy that requires best value standards. The research cannot recommend a specific implementation strategy, but it showed that the construction code should not just be blindly adopted.

Assumptions

Clear assumptions are critical in scientific research to narrow the scope of the research and to enable other researchers to repeat and validate the research. It is assumed that the key building parameters values selected provided adequate variation. The key building parameter values narrowed the scope to a manageable range to sufficiently investigate the research questions. Two assumptions were stated in Chapter 1 within the 'research scope' section, the assumption that the construction material has uniform qualities without defects or variation from typical values and the assumption that the operations and repair costs are primarily dependent on the building function instead of insulation material. The uniform construction materials assumption is an inherent assumption in BPS modeling as opposed to real world materials which may contain defects. However, manufacturing specifications and quality control limit the impact of these material defects on actual performance. Facilities usually do not have operations and repair costs for insulation, instead choosing to perform no maintenance on these materials until the time to replace them altogether. This assumption allows simplification of the life-cycle analysis to consider only the acquisition cost and energy operations cost.

Chapter 3 within part I, the assumption is made that the error in the heat balance caused by the BPS software's use of zoning is considered negligible since each simulation uses the same zoning configurations. This assumption was made in order to establish a model that could be used to address the research questions. Zoning and HVAC configuration would greatly expand this research to include additional factors and alternatives. Although meaningful to building energy optimization, this did not directly address the research question and would introduce additional complexities. Additional model settings that could be perceived as assumptions in the model can be found in Appendix A and Appendix B.

Additional assumptions during this research were made during the modeling and data analysis phase to enable comparisons between the simulations. One of the most important assumptions made was assuming a consistent HVAC system across all insulation levels in the modeling. A change in the HVAC size would create significant savings that would need to be included in the economic analysis. It was thought that the benefits would not be large enough from only changing the wall and roof insulation to merit downsizing the HVAC system. However, HVAC downsizing could occur when increased insulation was combined with other thermal energy efficiency factors that were not considered in this research effort.

Once the simulation data was collected, this assumption could be verified. The large facility located at Minot Air Force Base had the largest difference in annual energy between its construction standard configuration and any of its other fifteen insulation configurations. Using the sub-category breakdown in the BPS software results, the reduced load on the HVAC was calculated to be approximately 0.38 tons of cooling between these two insulation configurations. Since HVAC is typically sized in one ton or half ton increments for these sized facilities, this verifies that the HVAC system would not require downsizing. Since this location had the highest difference in annual operational energy, it validates this assumption for all key building parameters studied in this research. This assumption was critical to this research since non-constant HVAC systems would change the HVAC system input for the BPS software as well as the economic analysis performed.

Another assumption made during the analysis was that the material costs and energy costs remained constant throughout the life-cycle of the insulation. This assumption is obviously untrue since the economic market for these goods and services causes fluctuations in price. The research used the 2020 utility rates reported by the U.S. EIA as a constant price throughout the life-cycle analysis for each configuration. The actual impact of these price variation is likely negligible since this assumption was consistently made for every configuration. Additionally, the market prices for energy and insulation is unknown in the future. The uncertainty of estimating the changes outweighed the benefits to accuracy for the life-cycle analysis. This assumption drove the use of real interest rates instead of nominal interest rates during the analysis. Instead of using a nominal MARR of 2.4 which would include inflation, a real MARR of 0.4 was used to mirror the assumption made for the cost rate [63].

Lastly, an assumption made was that the BPS software accurately simulates building performance. Since this was the tool used to model the prototypical building performance, the inherent assumption is that the tool selected is appropriate and accurate. The pilot study was performed to reduce the risk of this assumption and select the appropriate BPS software for this research. EnergyPlus and Open Studio have frequently been used and validated in prior research providing a widely accepted level of accuracy for thermal energy analysis [17], [39]–[41], [43], [44].

Research Limitations

The primary limitations of this study include the scope of the research, lack of validation, and analysis based solely on cost. Time and complexity were the main factors preventing expanding these research limitations. These limitations could also be eliminated or minimized with future research efforts to build upon the model or expand the analysis. The limitations were appropriate to sufficiently answer the research questions for this study.

A significant limitation of this study is the lack of validation. Both EnergyPlus and OpenStudio are validated tools; however, they were not validated within this study for modeling USAF prototypical facilities. Using data from actual USAF buildings to compare the EnergyPlus estimates with actual energy usage would be a great method for validation. Unfortunately, this exceeded the scope of this thesis and could merit its own independent research effort. The focus of this research was a proof of concept for the economic viability of building code standards.

The complexity of a building envelope necessitated limiting the scope of the model. Varying too many parameters would prevent meaningful trends from being identified in the analysis. Instead, a majority of the factors affecting the energy flow through a building envelope were held constant to isolate the independent variables relationships. However, each parameter held constant limited the scope and prevented investigating its impact on energy flow. For example, the prototypical facilities used two-by-four construction when two-by-six construction could expand the insulations available. Although wall composition invites an intriguing comparison, it deviated from the research intent since most Air Force minor construction uses two-by-four construction. This is just one example of many where the BPS software inputs could be varied to expand the scope of this research.

Furthermore, the results should not be applied generally for all Air Force office facilities due to the wide variety of different office building designs and sizes. The three key building parameters of location, building size, and insulation materials should first be expanded to increase the applicability of the results. These key building parameters were intentionally selected to provide the proof of concept central to the research questions. But prior to policy implementation, more rigor should be performed to expand these key building parameters to improve the fidelity of the data results.

Another limitation of this research is that the analysis of the results was performed solely based on cost. The decision criteria for the best value construction was limited to only life-cycle cost. The economic analysis reveals the insulation material that provides the least monetary cost to the Air Force. However, other criteria could impact the material selection during construction. Air Force commanders, as the decision makers, may value other decision criteria over the life-cycle cost. For example, the acquisition cost could be so close to the statutory limit that increasing the initial construction cost would be prohibitive to the execution of the project due to Congressional appropriation limitations. Air quality and comfort for the building occupants could also be a non-monetary factor that could influence the insulation selection. Increased insulation could be selected to improve these non-monetary considerations. Other factors that were held constant in this study could also be affected by these non-monetary decision criteria such as amount of natural lighting, ventilation, shading, humidity control, and many more.

Research Benefits

This research provides insight into the energy performance of different insulation standards for Air Force facilities. The results indicated that construction code does not always provide the most cost-effective solution to building construction over the life-cycle of the facility. The results provided a positive proof of concept that construction codes should be investigated from a life-cycle cost perspective to determine the best economic value. In general, the information from this research could provide decision makers on how to implement different construction code standards within the Air Force to realize cost savings.

The four research questions proposed in chapter 1 were answered with the results of this study. The results positively affirmed that the research questions merited investigation. The construction code standard was shown not to be the most cost effective over the prototypical facilities life. The results indicated that the insulation material in construction should be considered with more scrutiny than merely adopting the minimum code requirement.

The purpose of this research was to identify opportunities for improved operational costs across the Air Force through facility construction. The results showed that increasing the wall insulation beyond the construction code would provide cost savings for both building sizes at every location studied. This provided a valuable trend that could be easily implemented within construction practice to recognize life-cycle cost savings. The roof insulation depended upon the size and location to whether exceeding the construction code would provide cost savings. Exceeding the construction code for the roof insulation with the large building was more cost effective in the cold and moderate climate locations, but not at the hot climate locations. The smaller facility did not benefit from exceeding the construction standard in the roof insulation, except in the cold climates. This showed that the best value roof insulation standard depended too much upon other factors to generalize a trend. However, the results provided enough positive results to affirm the research questions and merit further investigation and research.

The common-sense method for application of this research would be to codify the best-value standards within policy. Although this should eventually be the result of this research, caution is advised to not adopt the results in policy too quickly. More research should be taken to validate and expand this research prior to implementation. However, the benefits of the research are policies with a focus on sustainability that consider both environmental impact and economic considerations. Reducing the energy demand of Air Force facilities can coincide with lower life-cycle costs when prudently implemented. The results merited continued expansion of the research and shifting the focus of continued efforts to application and implementation.

Suggestions for Future Research

Future research should first focus on validating the BPS software results with actual Air Force building metrics. Validation of the results with real world Air Force buildings would provide insight into the accuracy of the model and bring increased confidence in the results. Prior to policy implementation, validation should occur to verify the applicability to actual facilities beyond the prototypical buildings used in this research.

Another important aspect for future research includes the influence of window type, insulation, and quantity on insulation performance. Windows remained constant in the simulations based on the prototypical facility from the Pacific Northwest National Laboratory [50]. However, windows are another key building parameter that could significantly affect the thermal energy flow through a building envelop and influence the economic benefit for the insulation. Similar to how electricity flows through the path of least resistance, heat will also transfer through the least insulated path. Windows provide an opportunity for this thermal bridging to occur since they typically have very low thermal resistance. Additionally, windows can cover a large portion of the wall surface area creating a large amount of heat transfer. For these reasons, studying the influence of windows on building performance is a logical and important next step.

Numerous future research efforts could explore increasing the key building parameters chosen and values used. Each input into the BPS model provides an opportunity to investigate the relationship of its impact to the results. Growing the number of variables changed would provide additional information on how these inputs interact with one another. In addition to increasing the variables changed in this model, the selected parameter values could also be expanded. For example, increasing the locations used in the model would make the results more applicable across the entire Air Force enterprise. The focus of the research could even shift to explore the economic value of other construction standards besides insulation.

Lastly, future research should consider the benefits to policy implementation. The results provided a positive proof of concept for the prototypical office building analyzed that more stringent standards than construction code could be adopted. Once future research validates and expands this research, the application directly to the Air Force should be analyzed. Proper implementation could provide cost savings across the Air Force organization. It is important to emphasize the limitation that these results cannot be generalized yet to other building sizes, locations, or types other than the ones studied in this model. But at the heart of this research is finding the best value standards to improve operational costs which can only be recognized with direct application and implementation.

Conclusion

The research goals were (a) to utilize BPS software to simulate and calculate the energy flow in a prototypical USAF office building, (b) to identify the potential energy consumption savings of different insulation standards for USAF prototypical office facilities, and (c) to determine which insulation standard is the most economically viable within the current market. The results of this study met the research goals and purpose. Due to the limitations of this research, a need for future validation studies and expansion of the research scope should be made prior to implementation of the results in policy. However, the results showed the opportunity for potential cost savings from applying the research results while simultaneously aligning with the growing energy conservation strategy in the DoD.

Currently the Air Force minor construction program typically uses LPTA acquisition contracts which cause most constructed office buildings to be built to the minimum construction code. The results showed that R-15 wall insulation which exceeded the code standard was more cost effective over the life-cycle of the prototypical office building. The R-60 roof insulation which significantly exceeded the code standard was most cost effective in the cold climates and with the large facility located in mild climates. Lower than standard roof insulation was most cost effective over the life-cycle in the hot climates and with the smaller facility in the mild climates. Future studies should be performed to expand the key building parameters of the simulation, investigate the interaction with window standards, expand the scope of the research, validate the model with a larger dataset, and discern the air quality differences from changing the insulation standard.

Designers, engineers, and policy makers in the Air Force need to consider facility life-cycle costs to lower annual facility sustainment costs. The results show that constructing to the minimum construction code is not the best economic value for the facility. Often exceeding the standard provides a lower life-cycle cost despite the higher acquisition cost for material and installation. This facility model and economic analysis, if validated and expanded, could provide a basis for a future tool that could be readily tested and implemented in Air Force construction or policy.

Appendix A: Summary of OpenStudio Simulation Inputs

Table A.1: Summary of OpenStudio Simulation Inputs for the large prototypical building located at Wright Patterson AFB

WBS	Category Name	Input Name	Input
1.1	Weather	Weather file	USA_OH_Dayton-Wright.Patterson.AFB.745700_TMY3
		ASHRAE Climate Zone	5A
		Calendar Year	2020
1.2	Life Cycle Costs	Analysis Type	Federal Energy Managemt Program (FEMP)
		Analysis Length	25 years
		NIST Fuel Escalation Rates	Yes
		NIST Region	MidWest
		NIST Sector	Commercial
1.3	Utility Bills	N/A	N/A
2.1	Schedule Sets	Default Schedules	Office Small Activity Schedule
			Office Small Building Occupancy Schedule
			Office Small Building Light Schedule
			Office Small Building Equipment Schedule
			Office Small Infiltration
2.2	Schedules	Office Small Activity Schedule	120 Watts/person
		Office Small Building Occupancy Schedule	Step starts at 0600 peaks at 0800-1600 with a dip at 1200 for lunch hour. Gradual step down after 1600.
		Office Small Building Light Schedule	10% emergency lighting assumed. Step starts at 0500 peaks at 0800-1700 with a more gradual step down. Affected with the lunch hour.
		Office Small Building Equipment Schedule	30% baseline use. Peaks at 0700 until 1700 with one step at 1800. Affected with the lunch hour.
		Office Small Infiltration	Value of 1.0 throughout the day

3.1	Construction Sets	Exterior Surface Construction	Exterior Wall
			Exterior Floor
			Exterior Roof
		Interior Surface Construction	Interior Wall
			Interior Floor
			Inerior Ceiling
		Ground Contact Surface Construction	Walls
			Floors
		Exterior Sub Surface Construction	Fixed Windows
			Operable Windows
			Doors
			Overhead Doors
			Skylights
			Tubular Daylight Domes
			Tubular Daylight Diffusers
		Interior Sub Surface Construction	Fixed Windows
			Operable Windows
			Doors
		Other Construction	Interior Partitions
3.2	Constructions	Exterior Surface Construction	Default Construction Layers
		Interior Surface Construction	Default Construction Layers
		Ground Contact Surface Construction	Default Construction Layers
		Exterior Sub Surface Construction	Default Construction Layers
		Interior Sub Surface Construction	Default Construction Layers
		Other Construction	Default Construction Layers
3.2	Materials	Default Construction Layers	Default Material Layers

4.1	People Definitions	People per Space Floor Area	0.06
		Fraction Radiant	0.3
		Sensible Heat Fraction	autocalculate
		Carbon Dioxide Generation Rate	.000038 L/s * W
	Lights Definition	Watts per Space Floor Area	10.763910 W/m2
		Fraction Radiant	0.7
		Return Air Fraction	0
		Fraction Visible	0.2
	Electric Equipment Definitions	Watts per Space Floor Area	6.781264 W/m2
		Fraction Latent	0
		Fraction Lost	0
		Fraction Radiant	0.5
	Internal Mass Definitions	Surface Area per Space Floor Area	2
5.1	Space Type	N/A	Default
6.1	Geometry	FloorspaceJS	PNNL Prototypical Office Building File
7.1	Building	N/A	Default
7.2	Stories	N/A	Default
7.3	Shading	N/A	Default
7.4	Exterior Equipment	N/A	Default
8.1	Properties	Thermal Zone	Attic
			Core Zone
			Perimeter Zone 1
			Perimeter Zone 2
			Perimeter Zone 3
			Perimeter Zone 4
8.2	Loads	Level 0	Lights - multipler 15
			Infiltration - multiplier 1
			Occupants - multipler 20
			Electric equipment - multipler 25
			Office outlet plugs - multiplier 25
8.3	Surfaces	N/A	Default
8.4	Subsurfaces	N/A	Default
8.5	Interior Particians	N/A	Default
8.6	Shading	N/A	Default

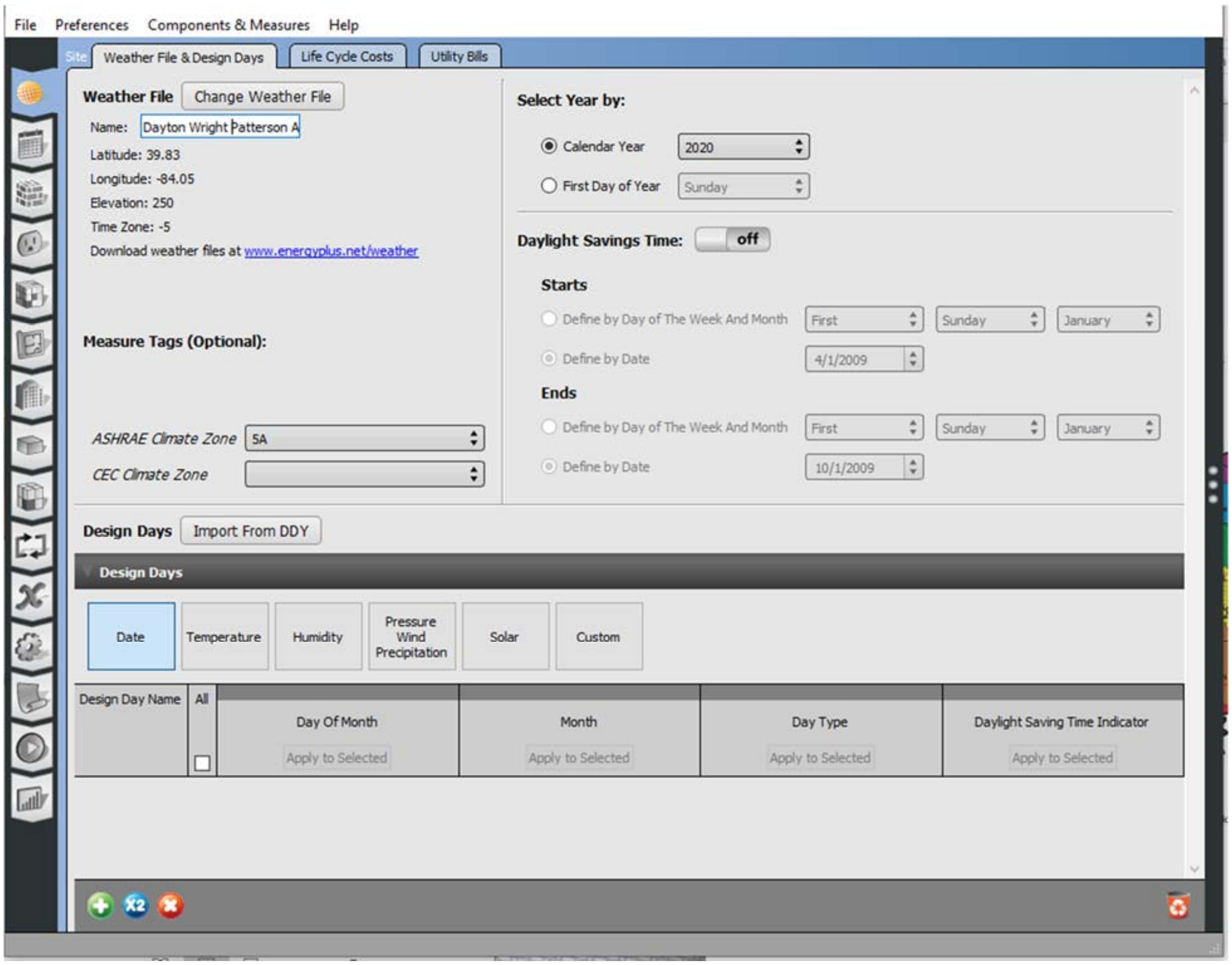
9.1	HVAC Systems	N/A	Default
9.2	Cooling Sizing Parameters	N/A	Default
9.3	Heating Sizing Parameters	N/A	Default
10.1	HVAC Systems	Layout Configuration	Centralized, packaged unit; Ducted with heating and cooling coils
11.1	Output Variables	Possible Output Variables	Default (546 of 571 options)
12.1	Simulations Settings		
	Run Period	Date Range	January 1 through December 31
		Heaing Sizing Factor	1.25
		Cooling Sizing Factor	1.15
		Number of timesteps per hour	4
	Radiance Parameters	Parameters	Coarse
	Simulation Control	Do Zone Sizing Calculations	Off
		Do Plant Sizing Calculations	Off
		Run Simulation for weather file	On
		Minimum Warmup Days	6
		Temperature Convergence Tolerance	0.2
		Do System Sizing Calculations	Off
		Run Simulation for Sizing Periods	Off
		Maximum Warmup Days	25
		Loads Convergence Tolerance Value	0.04
		Solar Distribution	Full Interior and Exterior
	Program Control	N/A	N/A
	Output Control Reporting Tolerances	Time Heating Setpoint Not Met	0.2
		Time Cooling Setpoint Not Met	0.2
	Convergence Limits	Maximum HVAC Iterations	20
		Maximum Plant Iterations	8
		Minimum Plant Iterations	2
		Minimum System Timestep	1
	Shadow Calculations	Calculation Frequency	7
		Maximum Fugures in Calculation	15000
	Inside Surface Convection Algorithm	Algorithm	TARP
	Outside Surface Convection Algorithm	Algorithm	DOE-2
	Heat Balance Algorithm	Surface Temp Upper Limit	200
		Maximum Surface Convection Heat Transfer Coefficient	1000
		Minimum Surface Convetion Heat Transfer Coefficient	0.1
		Algorithm	Conduction Transfer Function
	Zone Heat Balance Algorithm	Algorithm	Third Order Backward Difference
	Zone Air Contaminant Balance	CO2 Concentration	Off
	Zone Capacitance Multiple Research Special	Temperature Capacity Multiplier	1
		CO2 Capacity Multiplier	1
		Humidity Capacity Multiplier	1
13.1	Measures	N/A	N/A
14.1	Run Simulation	None	None
15.1	Results Summary	None	None

Appendix B: Visual Documentation of Inputs for OpenStudio Simulations

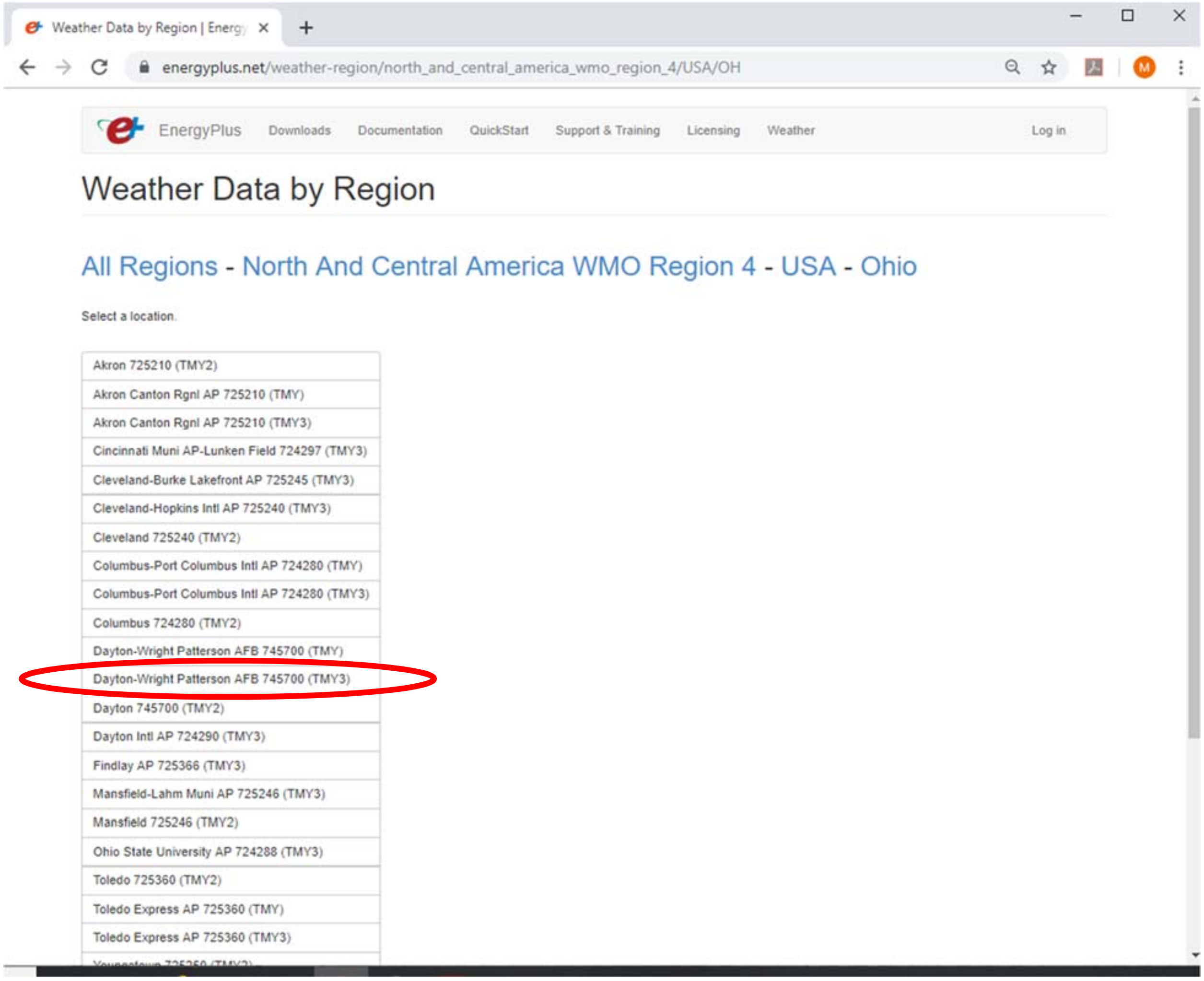
<u>Simulation:</u> Small prototypical USAF office building at WPAFB Dayton, OH

<u>Energy Plus Simulation using Open Studio</u>

1. **Weather**
   a. Weather File & Design Days

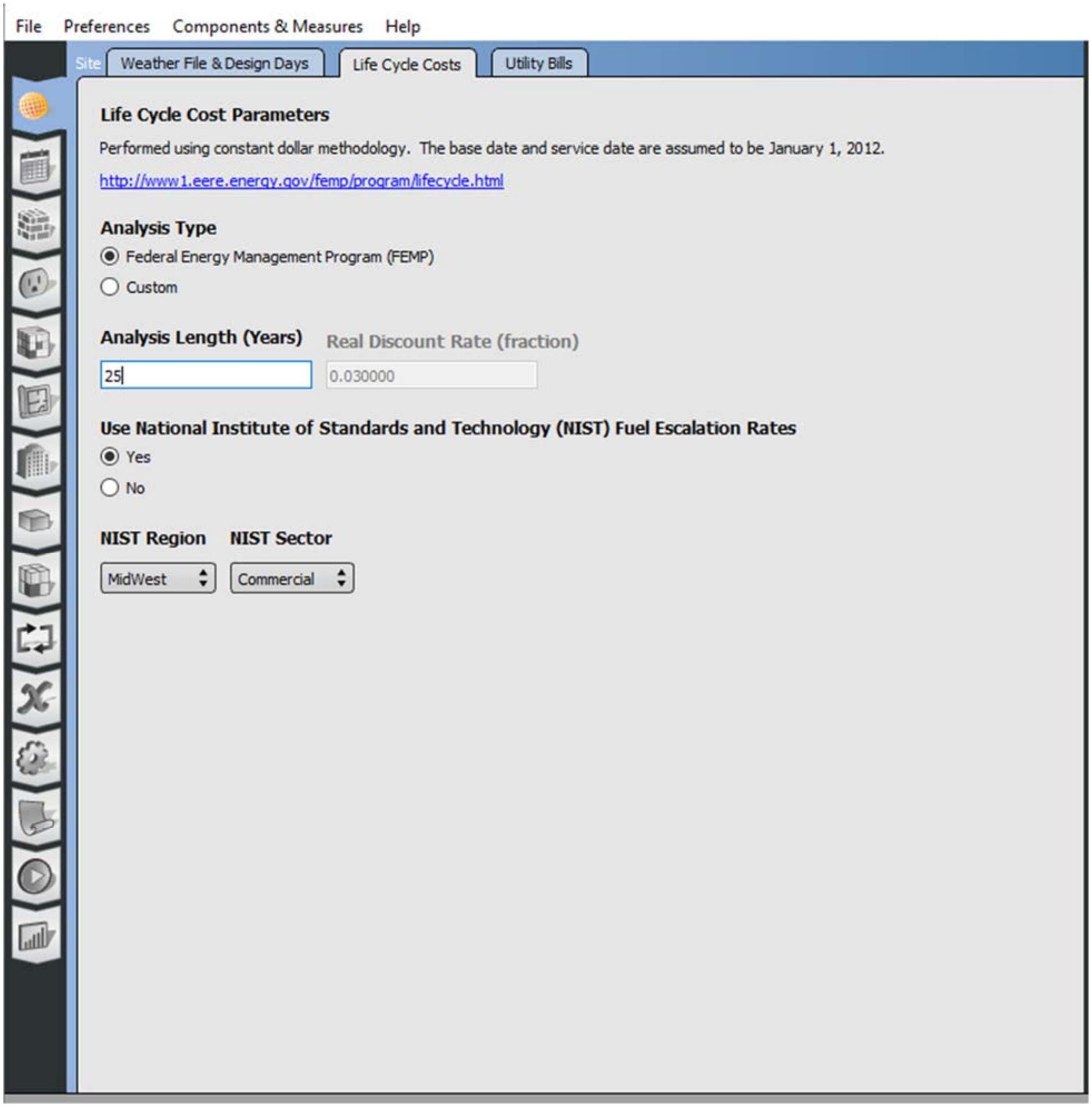


Weather data file for WPAFB downloaded at energyplus.net/weather.



ASHRAE Climate: 5A
CEC Climate Zone: N/A (California)
Design Days – N/A (for sizing HVAC capacity)

b. Life-cycle Costs



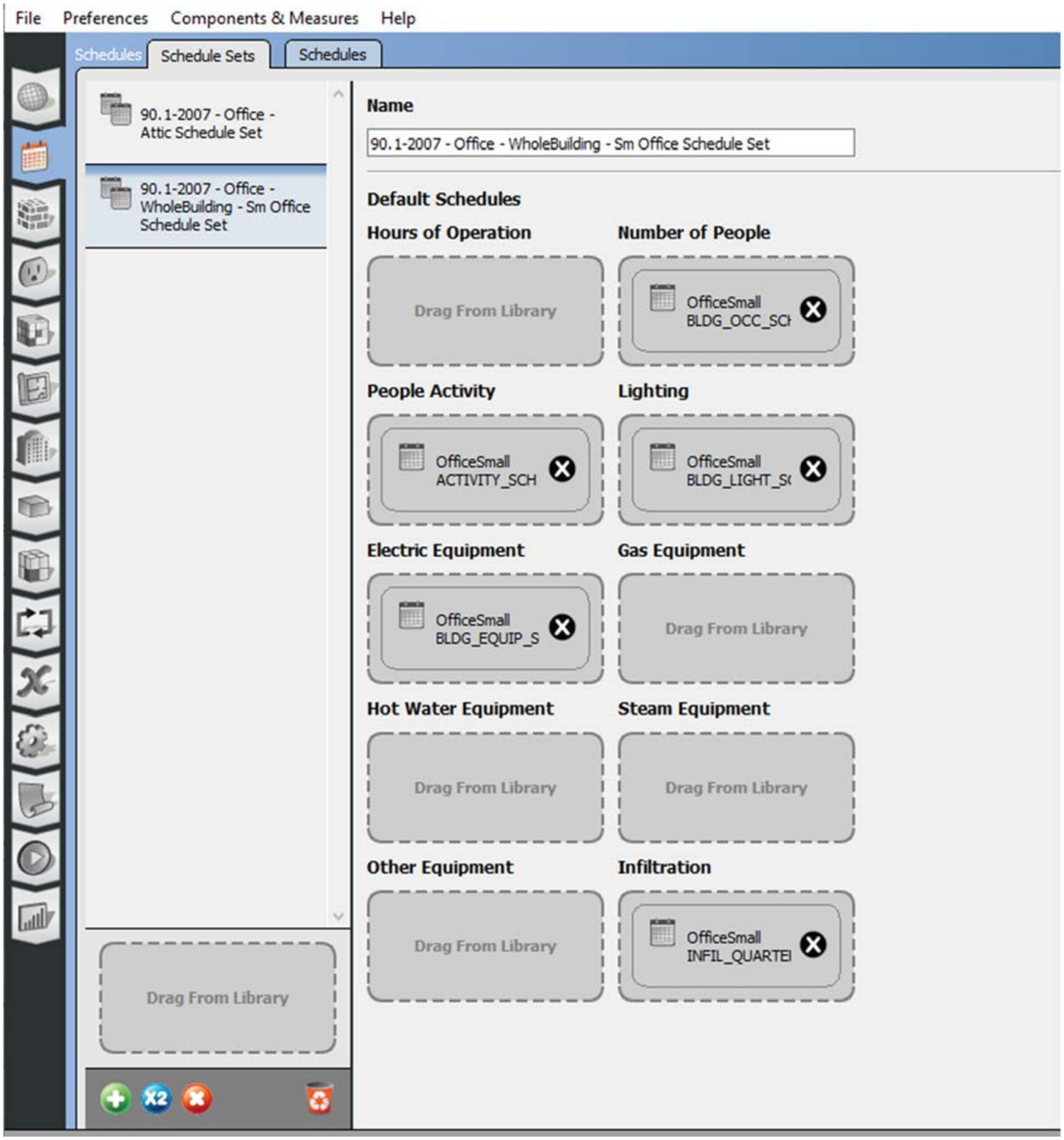
National Institute of Standards and Technology (NIST) Fuel Escalation Rates

- Based on energy forecasted data from the Energy Information Administration (EIA) of the US Department of Energy (DOE)
- https://www.nist.gov/programs-projects/fuels
- Age: 25 years at which point roof, HVAC, windows, and insulation should be replaced meriting a full renovation project.
- Ohio is in Midwest and office space is considered commercial

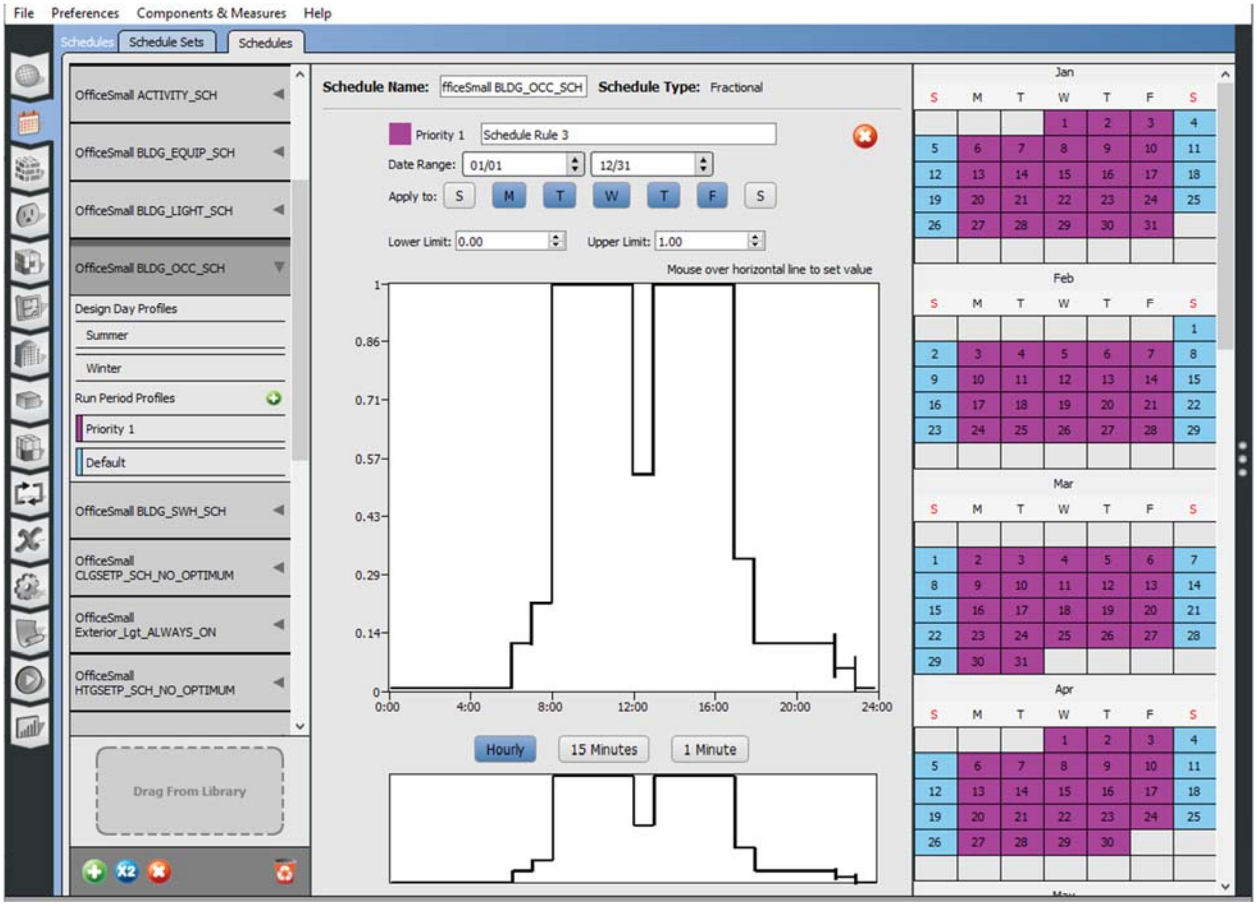
c. Utility Bills – Not Used

2. Schedules

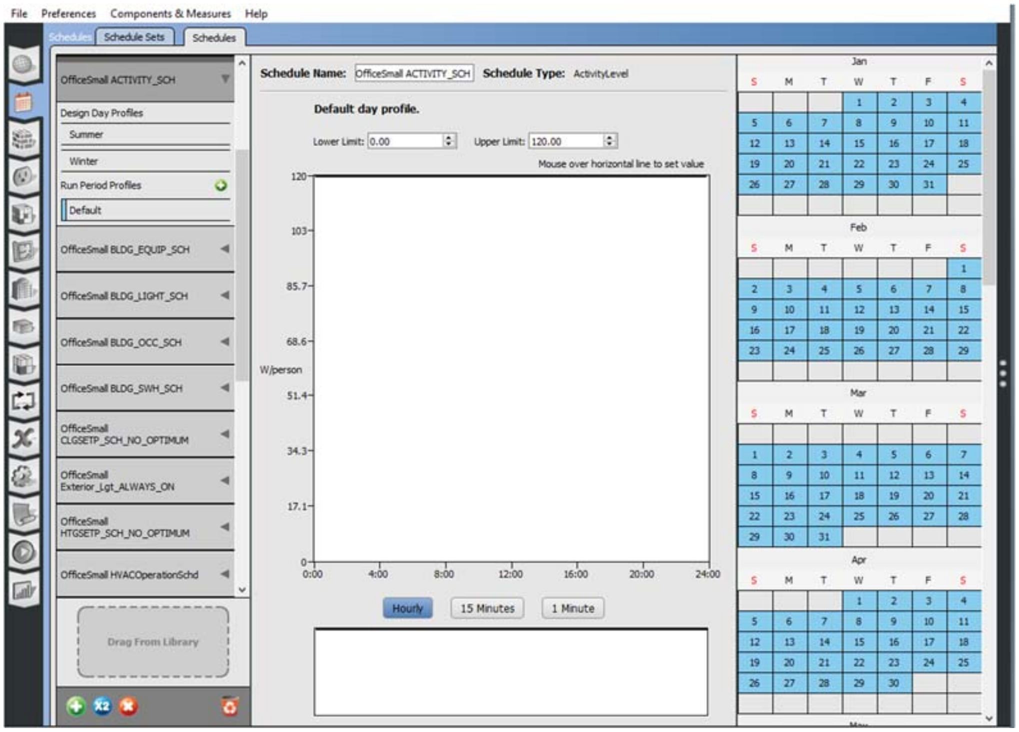
a. Schedule Sets



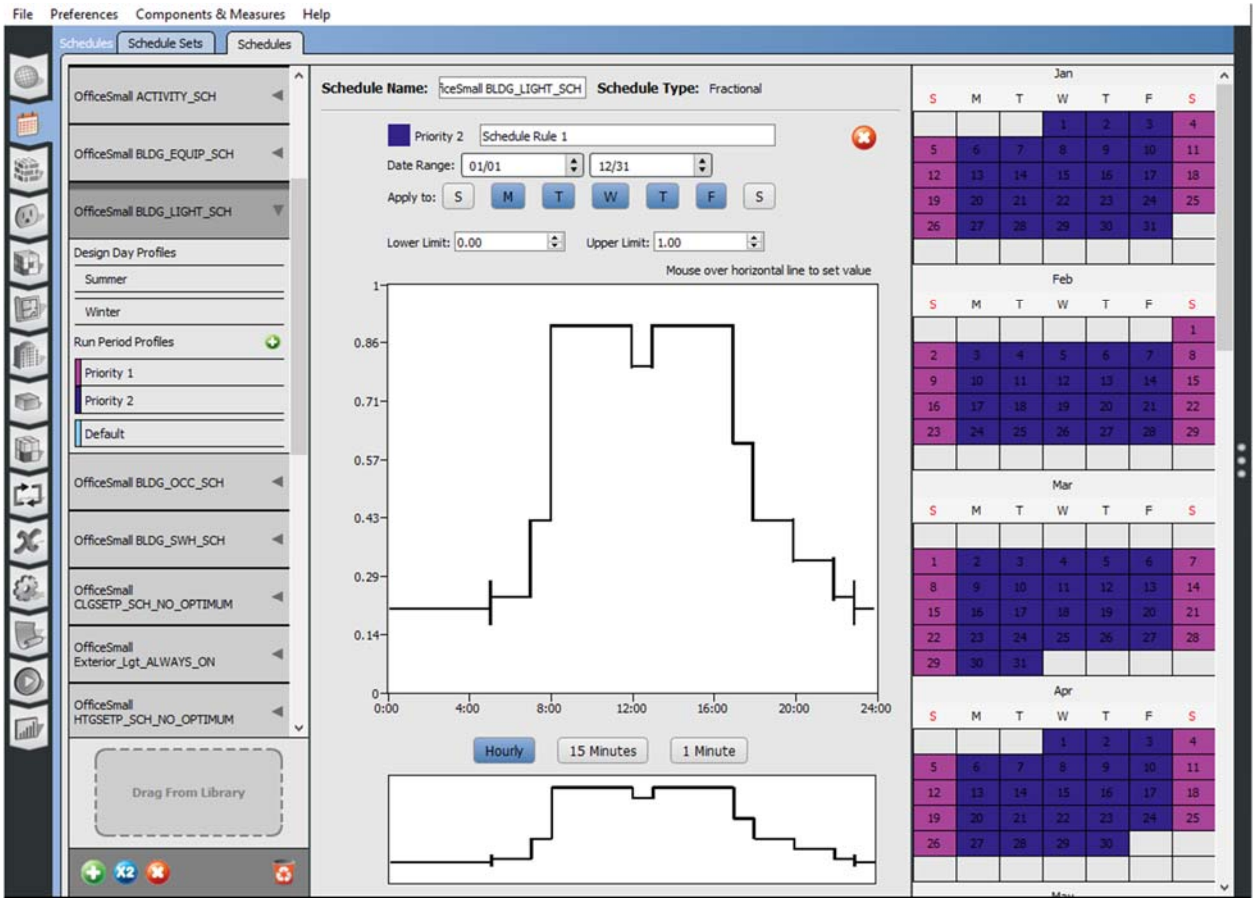
b. Schedules



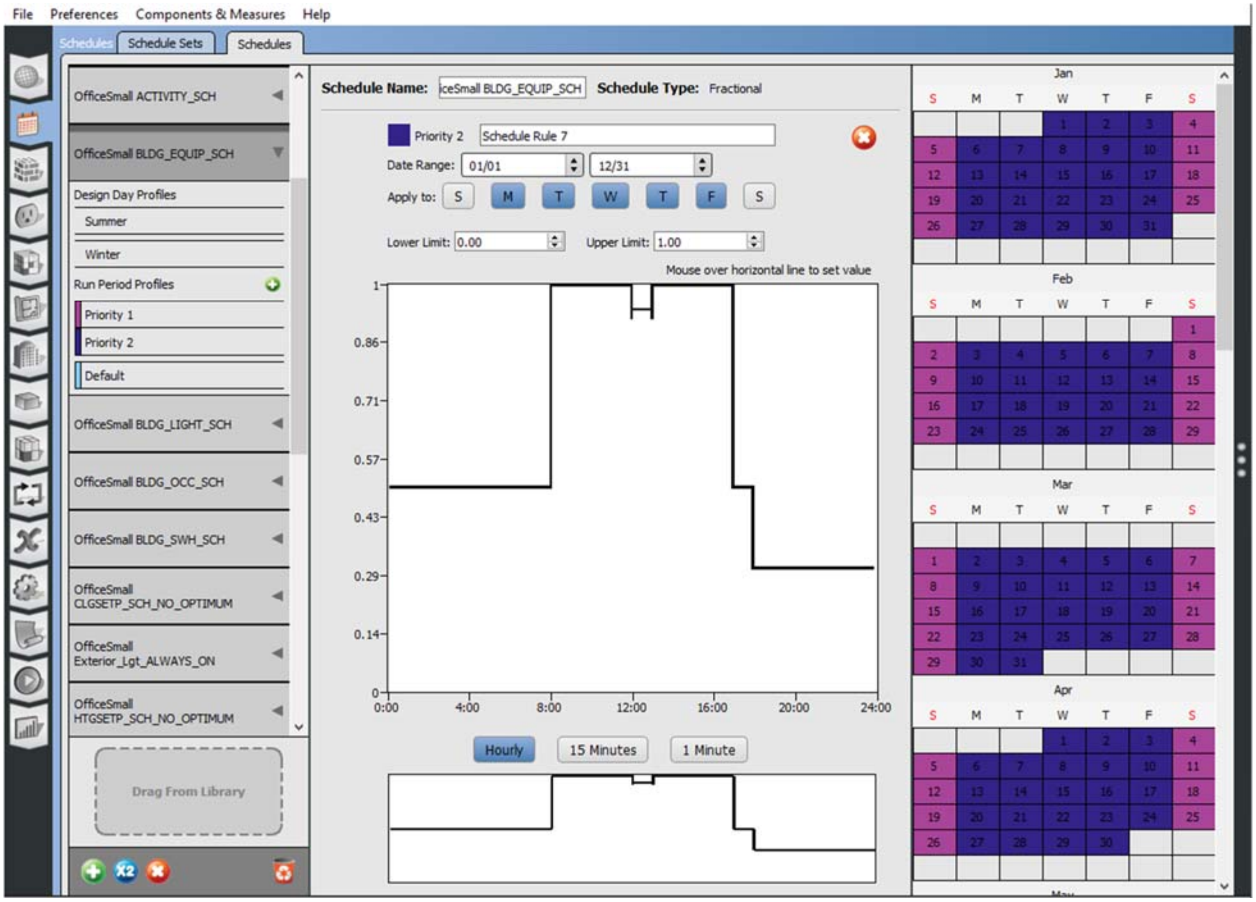
Occupancy loads (people) based off prototypical commercial office. Occupancy core hours between 8 and 5 with a dip during lunch hour.



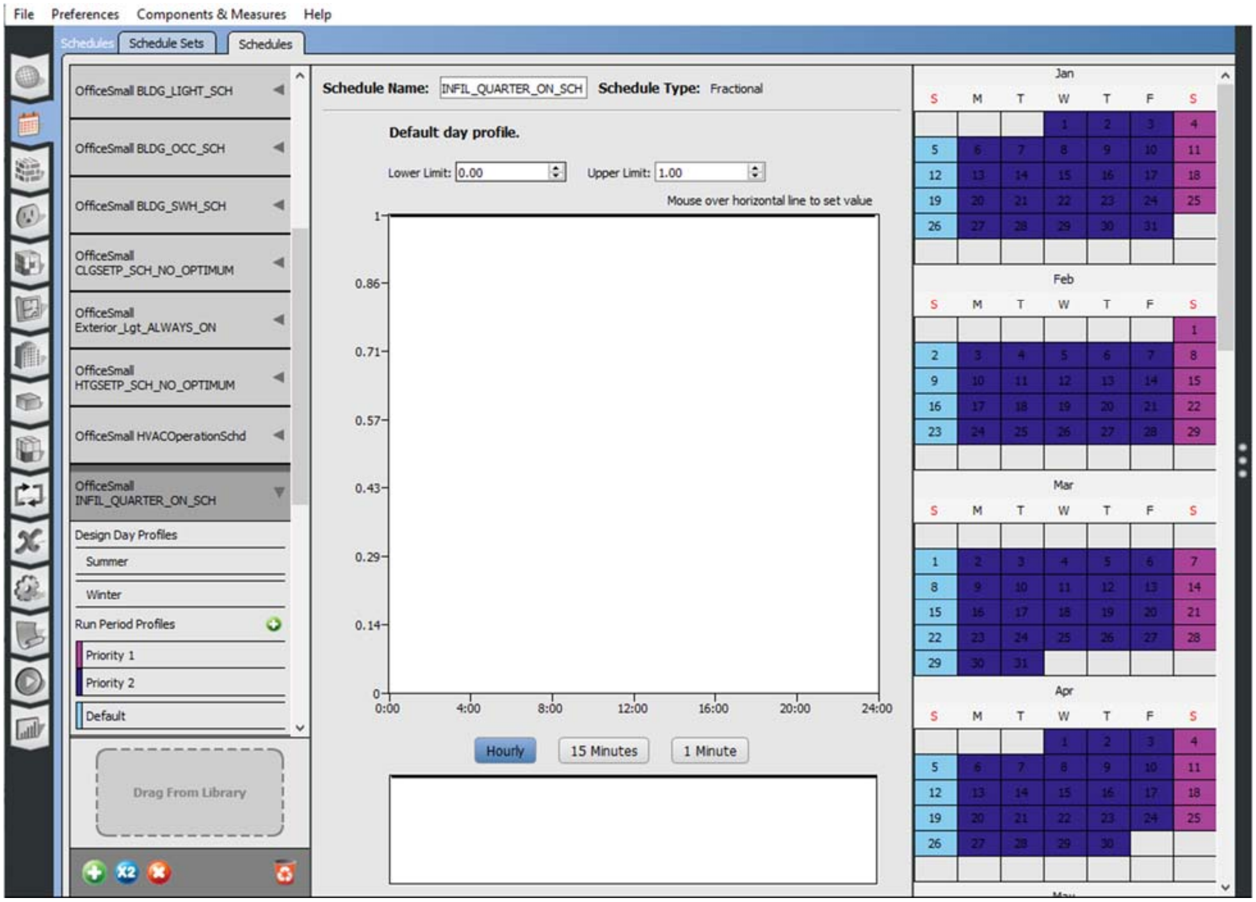
All occupants assumed to be working at computers or seated with low activity level: 120 W/person



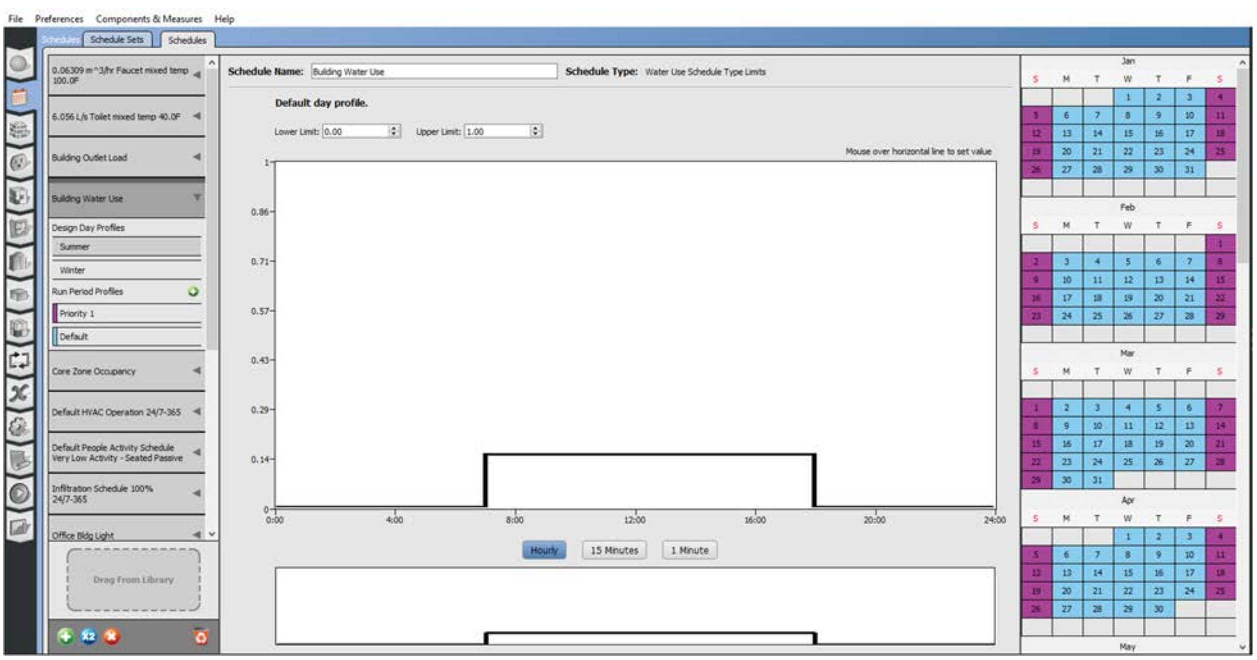
Light schedule based off prototypical commercial office. Emergency lighting accounts for 15% of lighting that remains on all the time. Otherwise, follows the occupancy curve.



Small office equipment based off prototypical commercial office. The load is expected to follow a similar curve to occupancy with a baseline of 30%.



Infiltration assumed to be constant at 100%.

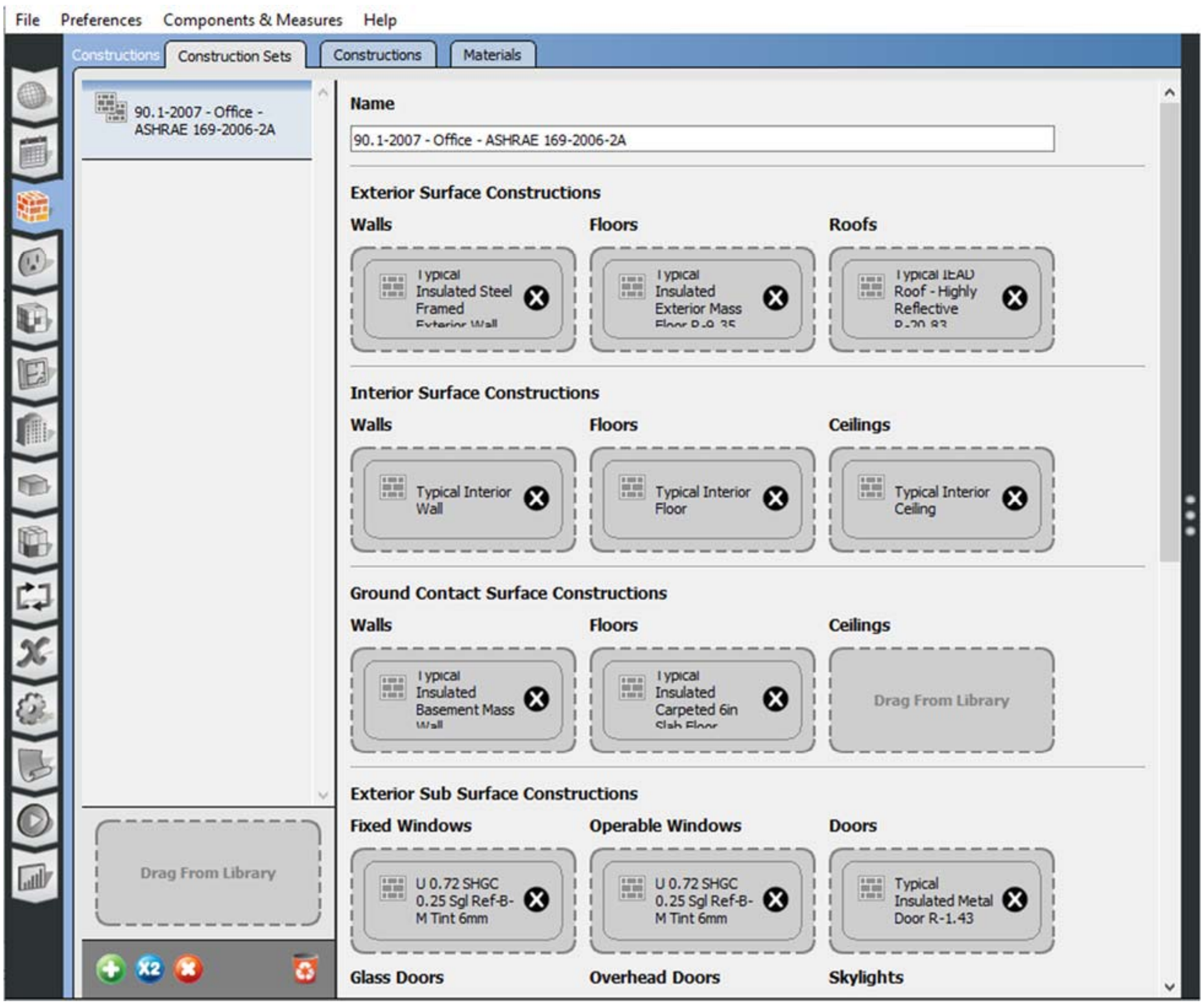


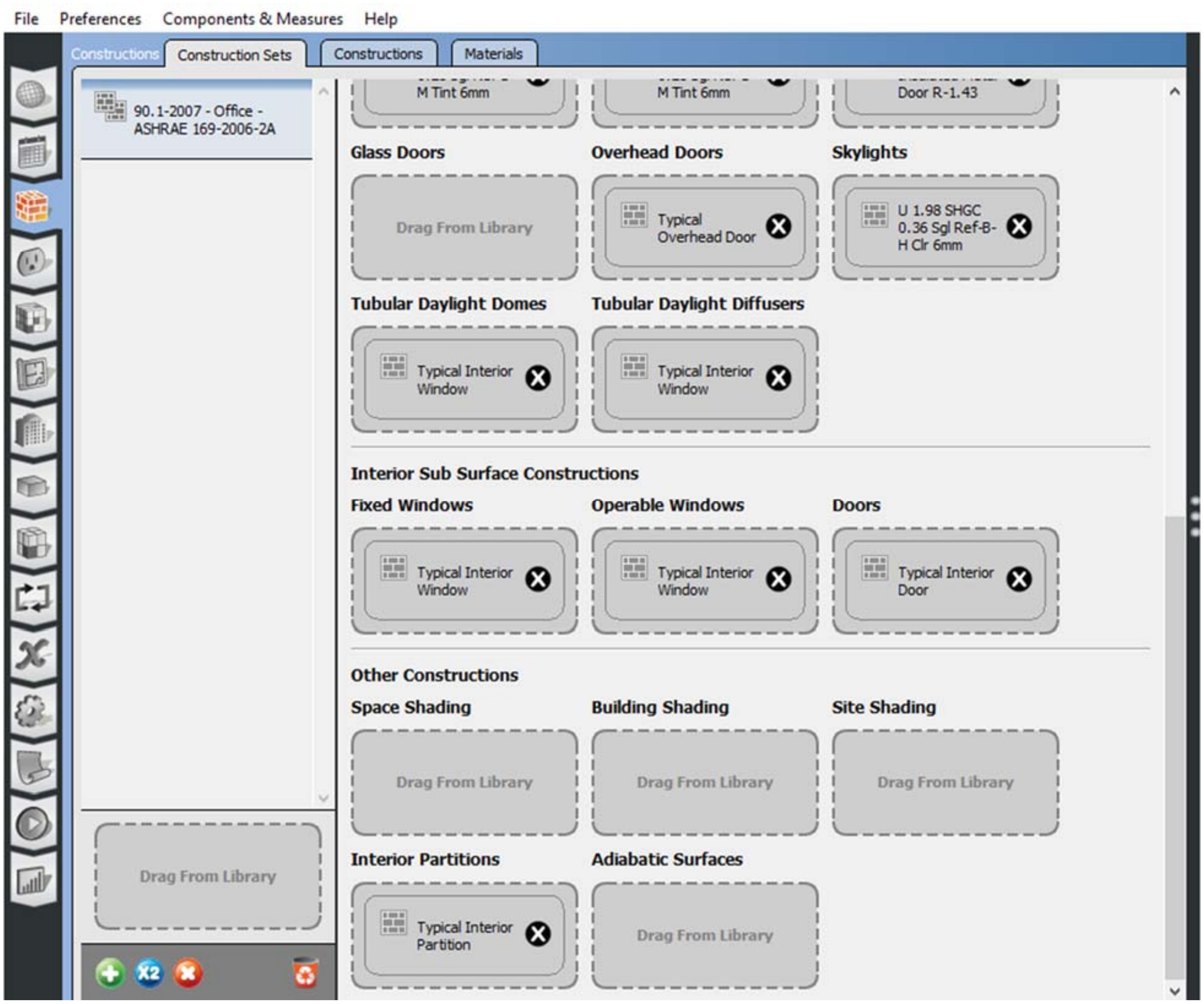
Water use determined to follow core operational hours. Only a fraction of full building capacity used, 15%. Normally water fixtures remain in the off position except for the small amount of time it is being used.

3. Constructions

a. Construction sets

The model is primarily concerned with the construction envelope. As such the model included the construction buildout for the walls, floors, roof, windows, interior partitions, and doors.



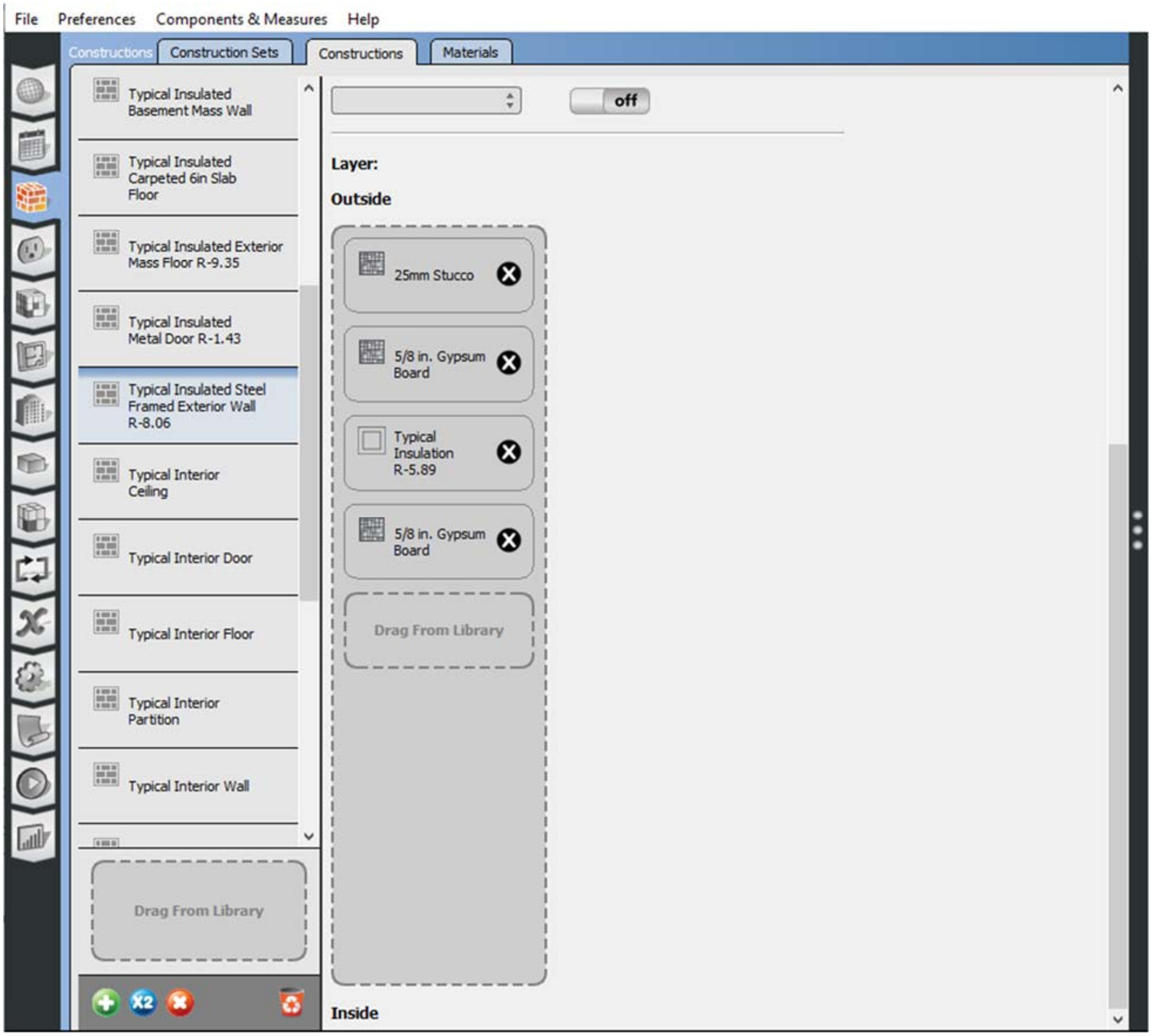


b. Constructions

The below screenshot provides an example of one construction set: the exterior wall.

This construction set considers the materials that make up the exterior wall: The 25 mm stucco, 5/8’’ gypsum board, R-5.89 batt insulation, and another 5/8’’ gypsum board.

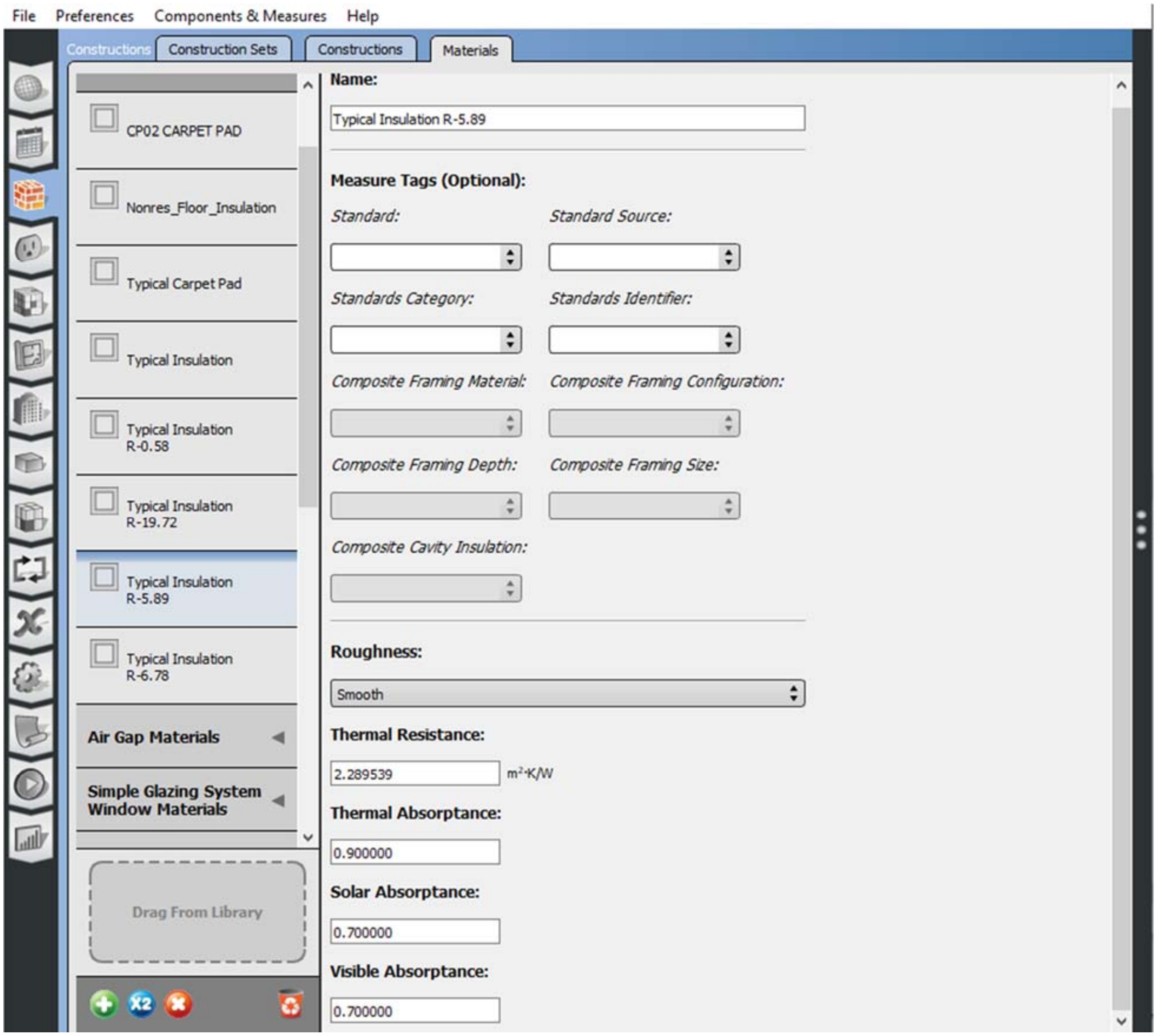
A breakdown similar to this one was created for each construction set listed above.



c. Materials

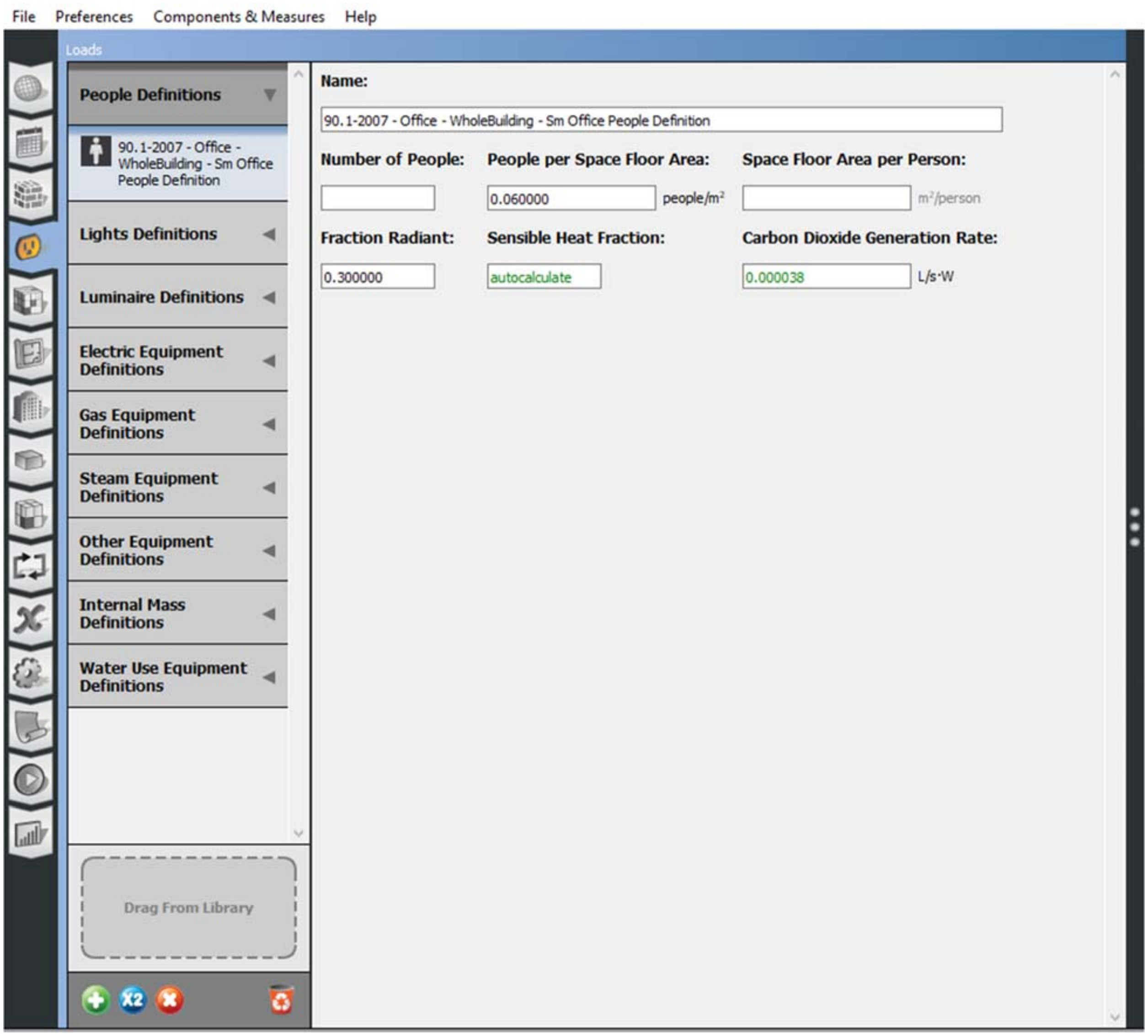
This provides an example of one construction material: the wall insulation.

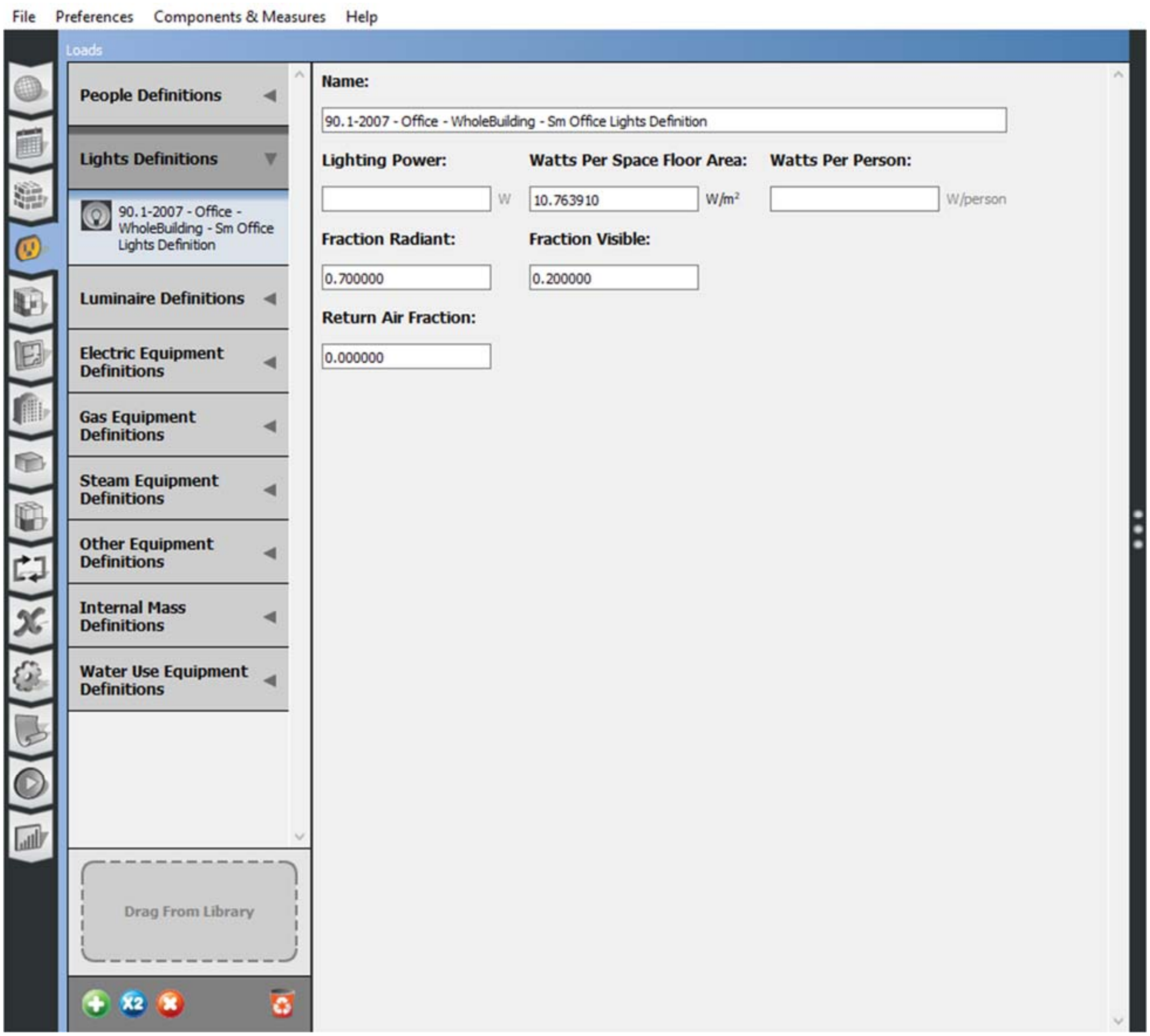
This construction material provides attributes of the construction material that are relevant to the energy model such as thickness, conductivity, density, absorption, etc. The default insulation was R-5.89 based on the prototypical office building. However, the thermal resistance value is manually changed to reflect the insulation configurations needed for this research. The 2.289539 thermal resistance equates to R-13 insulation.

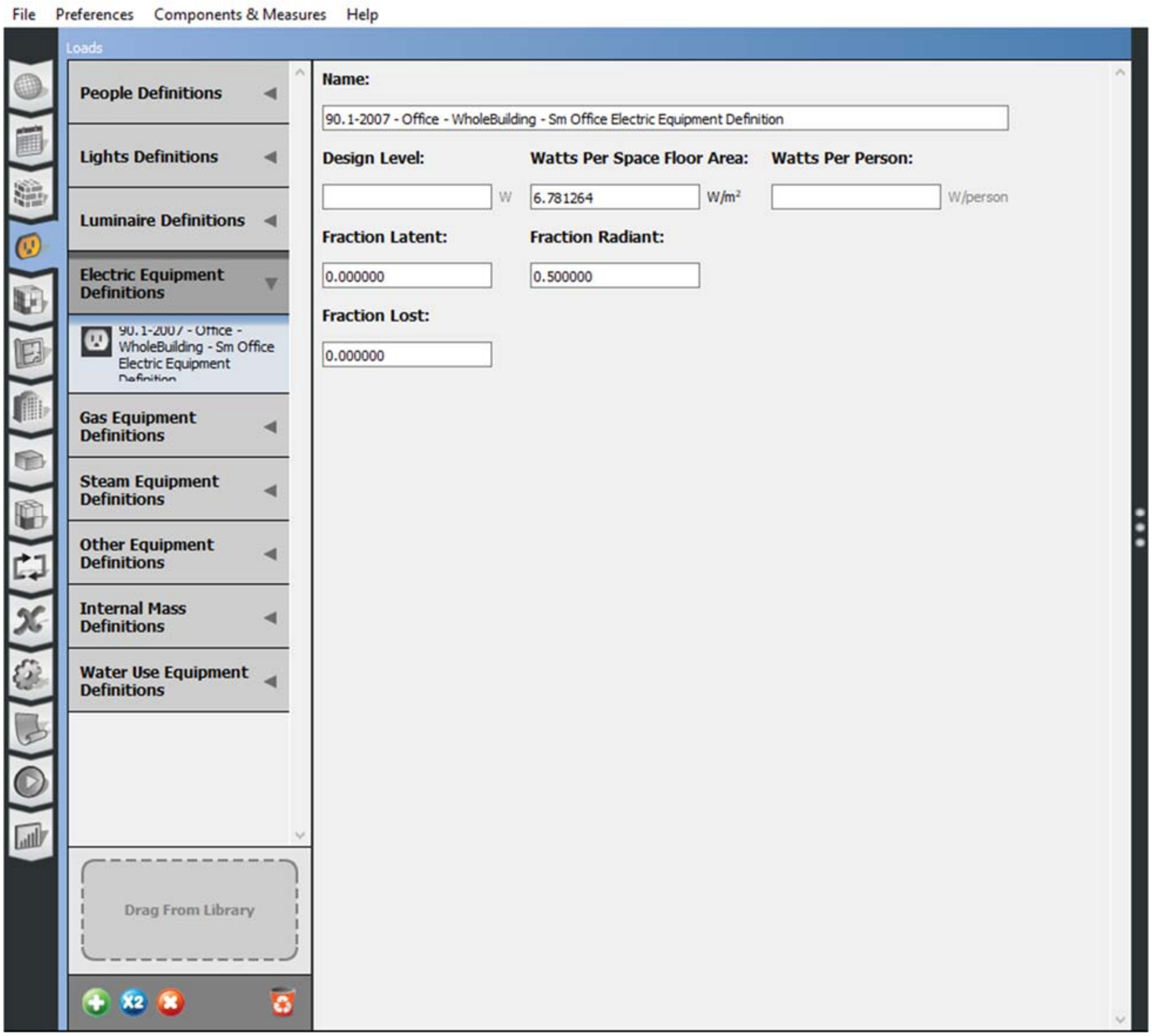


4. Loads

Three internal loads were included in this model: occupancy or people generating heat, lighting generating heat, and electrical equipment generating heat. The three screenshots are shown below. The lighting values will need to be adjusted from fluorescent to LED for the research thesis since the Air Force has adopted the standard of LED lighting in facilities.

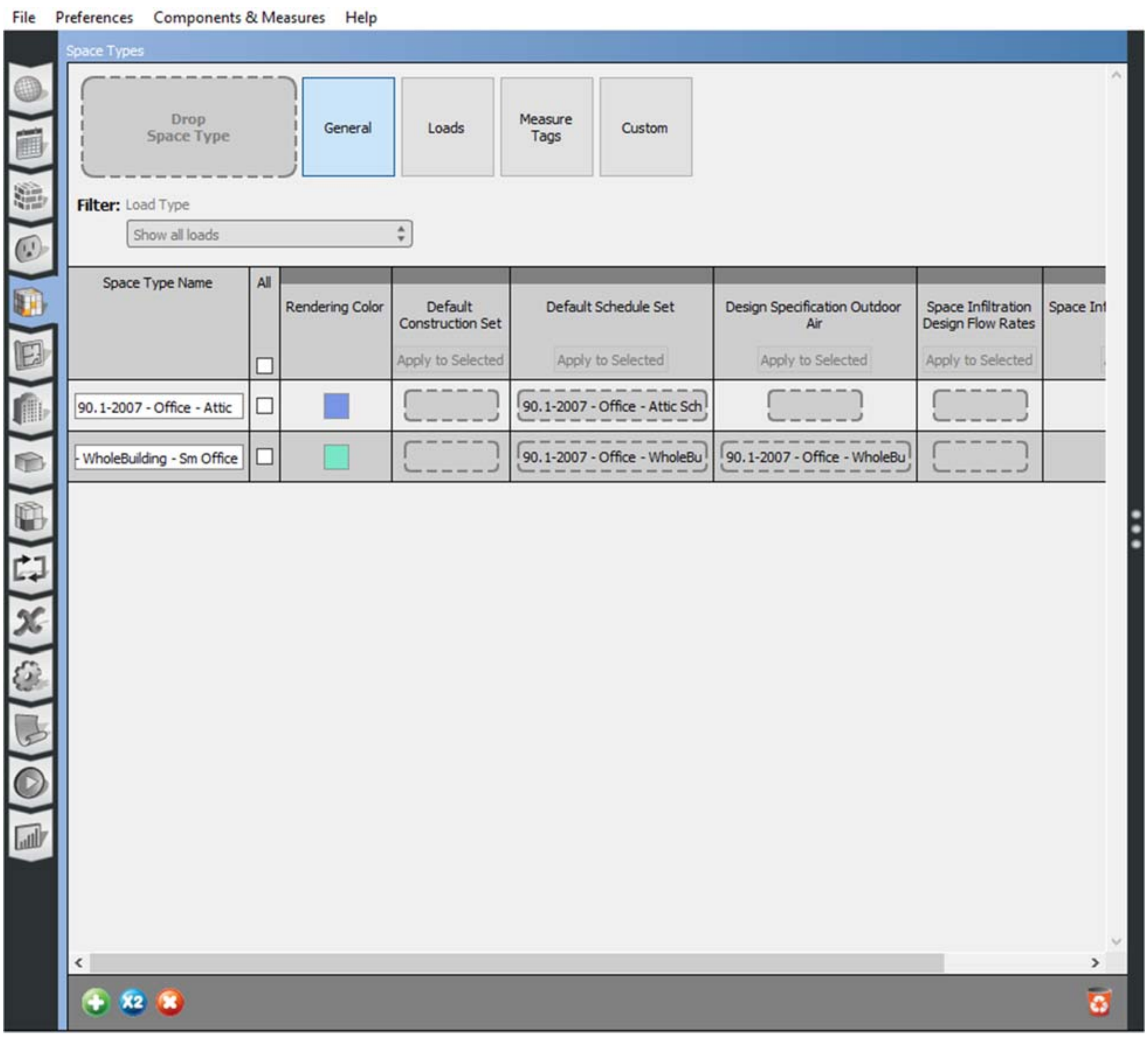

File Preferences Components & Measures Help
Loads
People Definitions
90.1-2007 - Office - WholeBuilding - Sm Office People Definition
Lights Definitions
Luminaire Definitions
Electric Equipment Definitions
Gas Equipment Definitions
Steam Equipment Definitions
Other Equipment Definitions
Internal Mass Definitions
Water Use Equipment Definitions
Drag From Library
Name:
90.1-2007 - Office - WholeBuilding - Sm Office People Definition
Number of People:
People per Space Floor Area:
0.060000
people/m²
Space Floor Area per Person:
m²/person
Fraction Radiant:
0.300000
Sensible Heat Fraction:
autocalculate
Carbon Dioxide Generation Rate:
0.000038
L/s·W


File
Preferences
Components & Measures
Help
Loads
People Definitions
Lights Definitions
90.1-2007 - Office - WholeBuilding - Sm Office Lights Definition
Luminaire Definitions
Electric Equipment Definitions
Gas Equipment Definitions
Steam Equipment Definitions
Other Equipment Definitions
Internal Mass Definitions
Water Use Equipment Definitions
Drag From Library
Name:
90.1-2007 - Office - WholeBuilding - Sm Office Lights Definition
Lighting Power:
W
Watts Per Space Floor Area:
10.763910
W/m²
Watts Per Person:
W/person
Fraction Radiant:
0.700000
Fraction Visible:
0.200000
Return Air Fraction:
0.000000



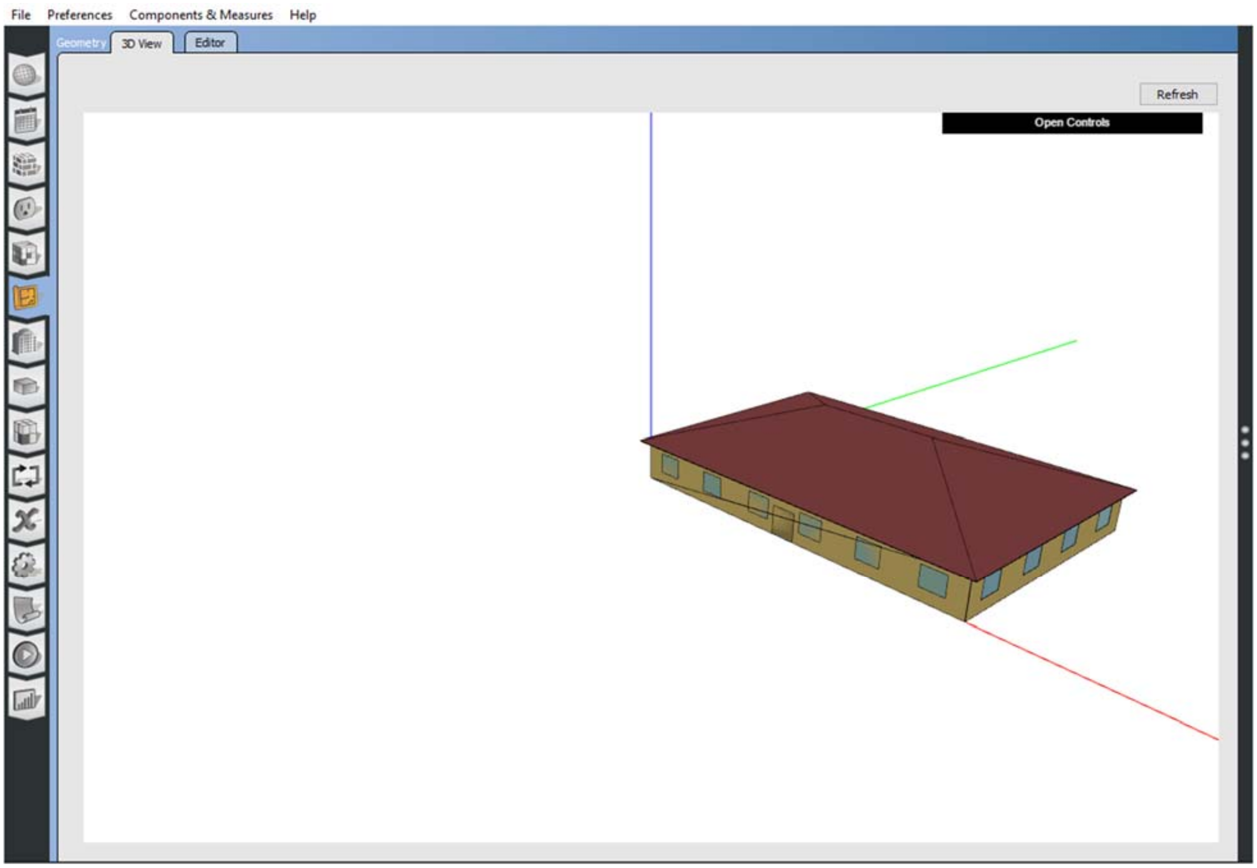
5. Space Types

This section's details are not required since only the building envelope is considered. The internal loads are required to size HVAC ducting and internal air flows, but this is not included in this research scope.



6. Geometry

A prototypical building geometry is used for this thesis developed by PNNL. A visual of the small facility is shown below.

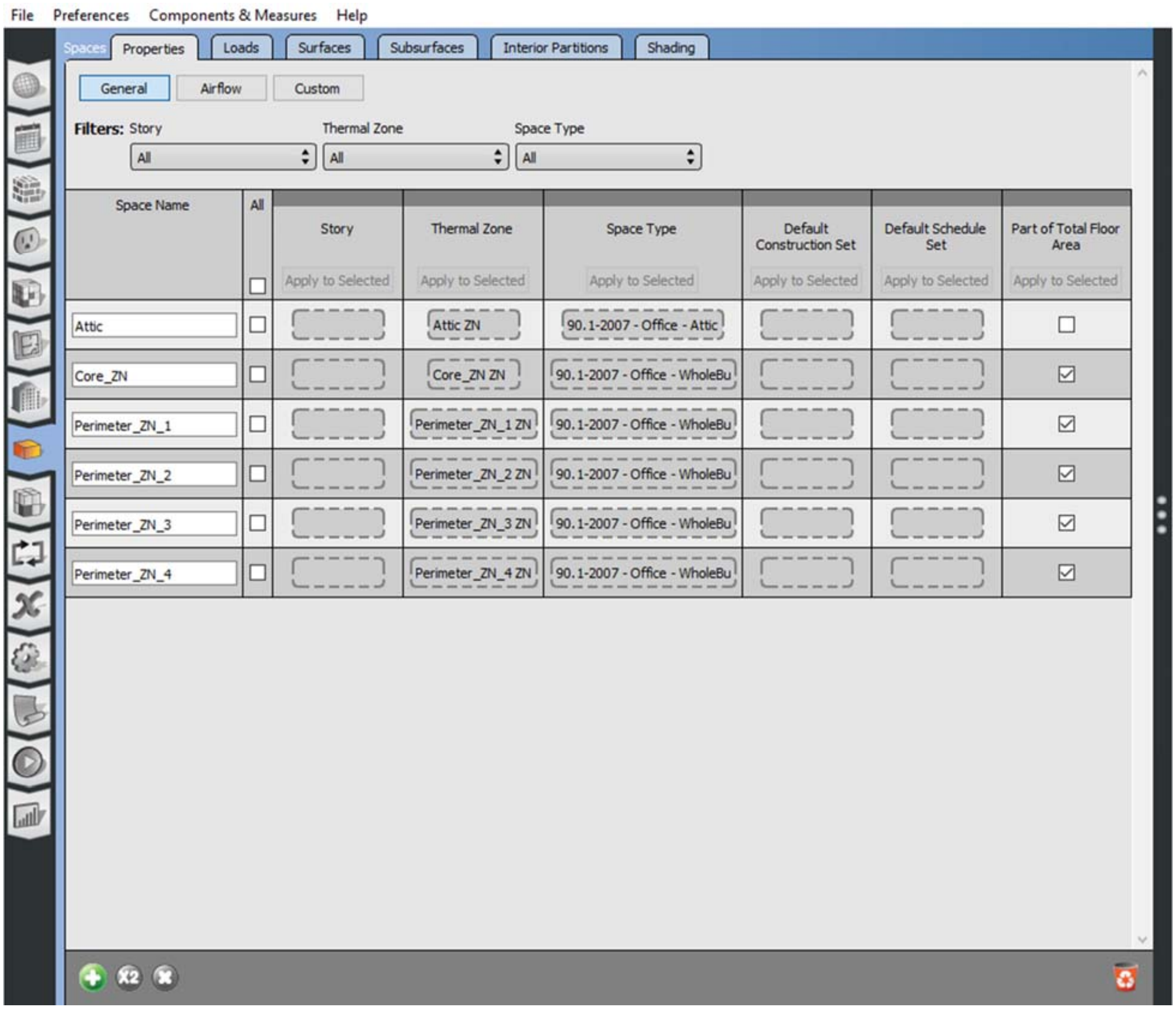


7. Facility

The facility section describes overall building attributes. The default values were kept for this section. Shading and exterior equipment was not considered for this research scope.

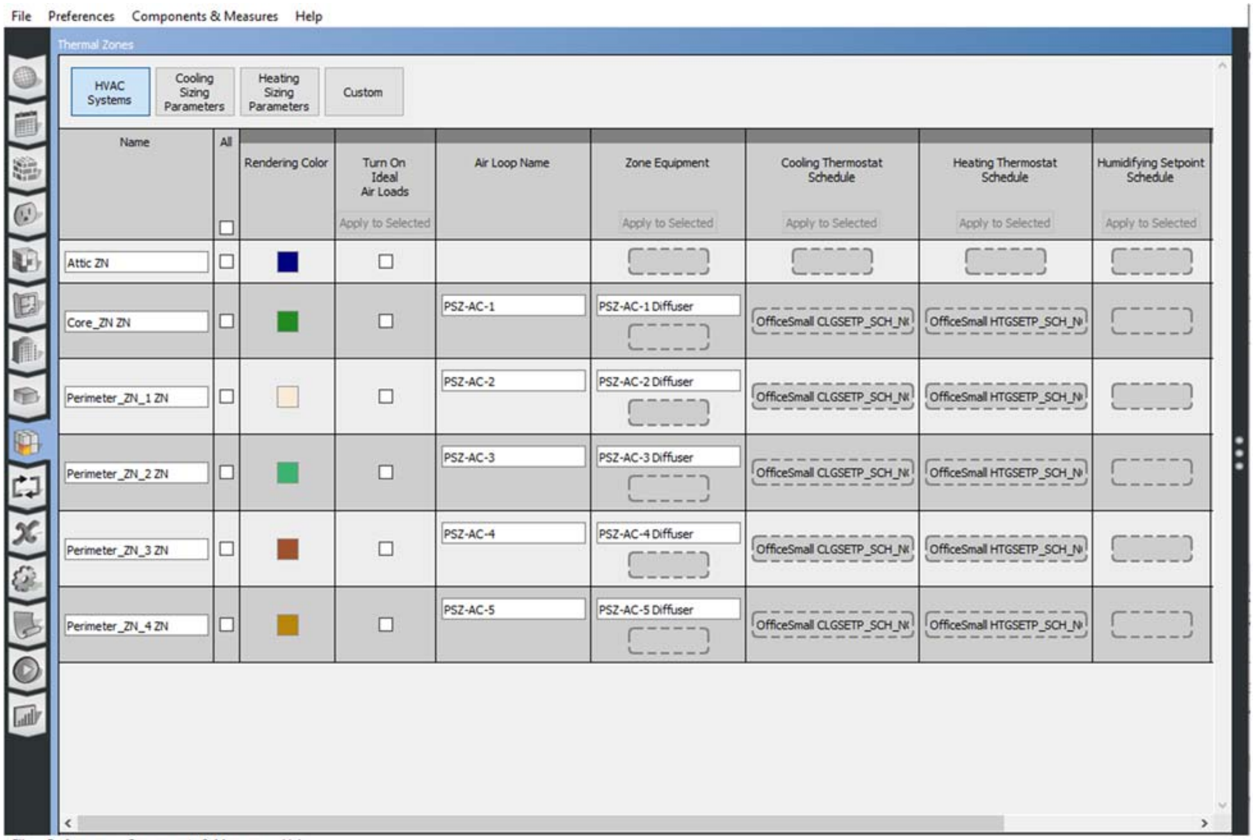
8. Spaces

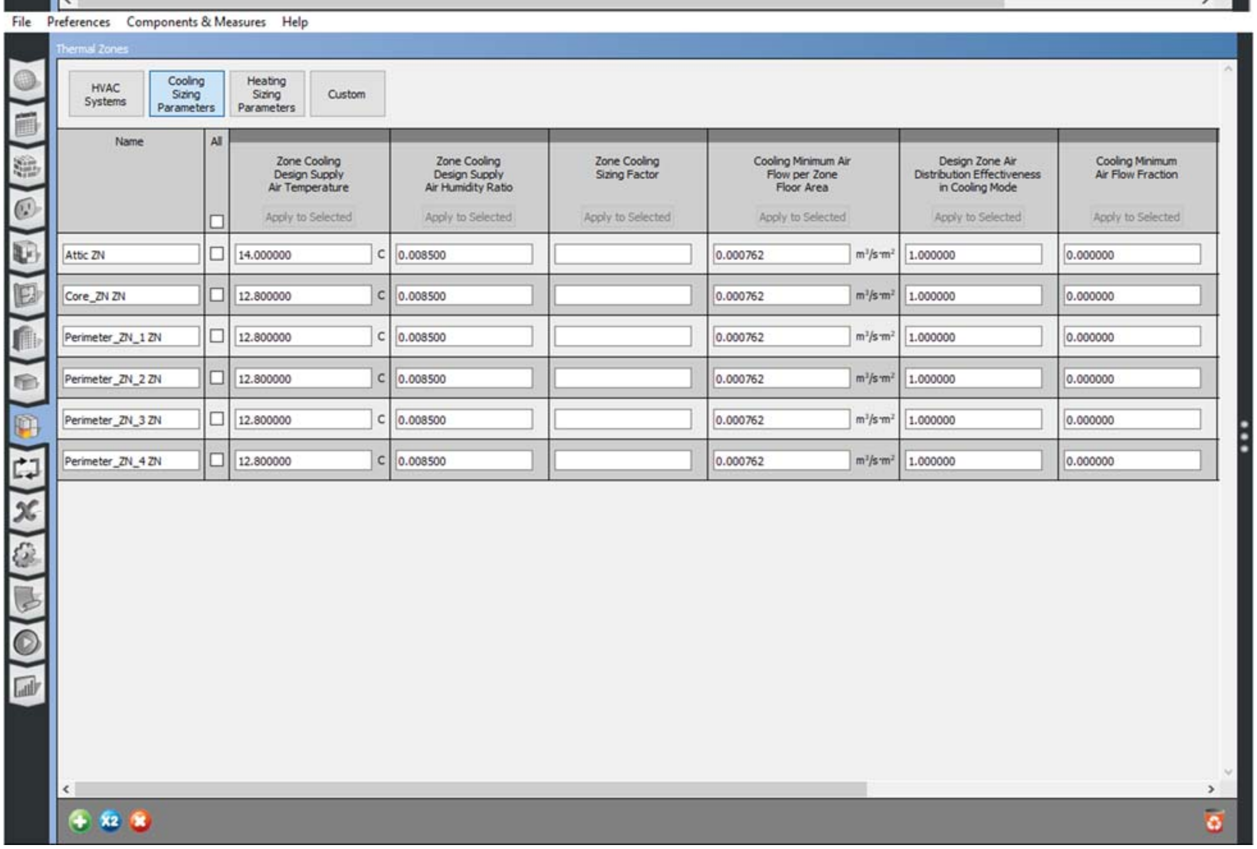
Similar to space types, this was not required since only the building envelope is considered. The internal loads are required to size HVAC ducting and internal air flows, but this is not included in this research scope. The default values from the prototypical building were kept for this section.

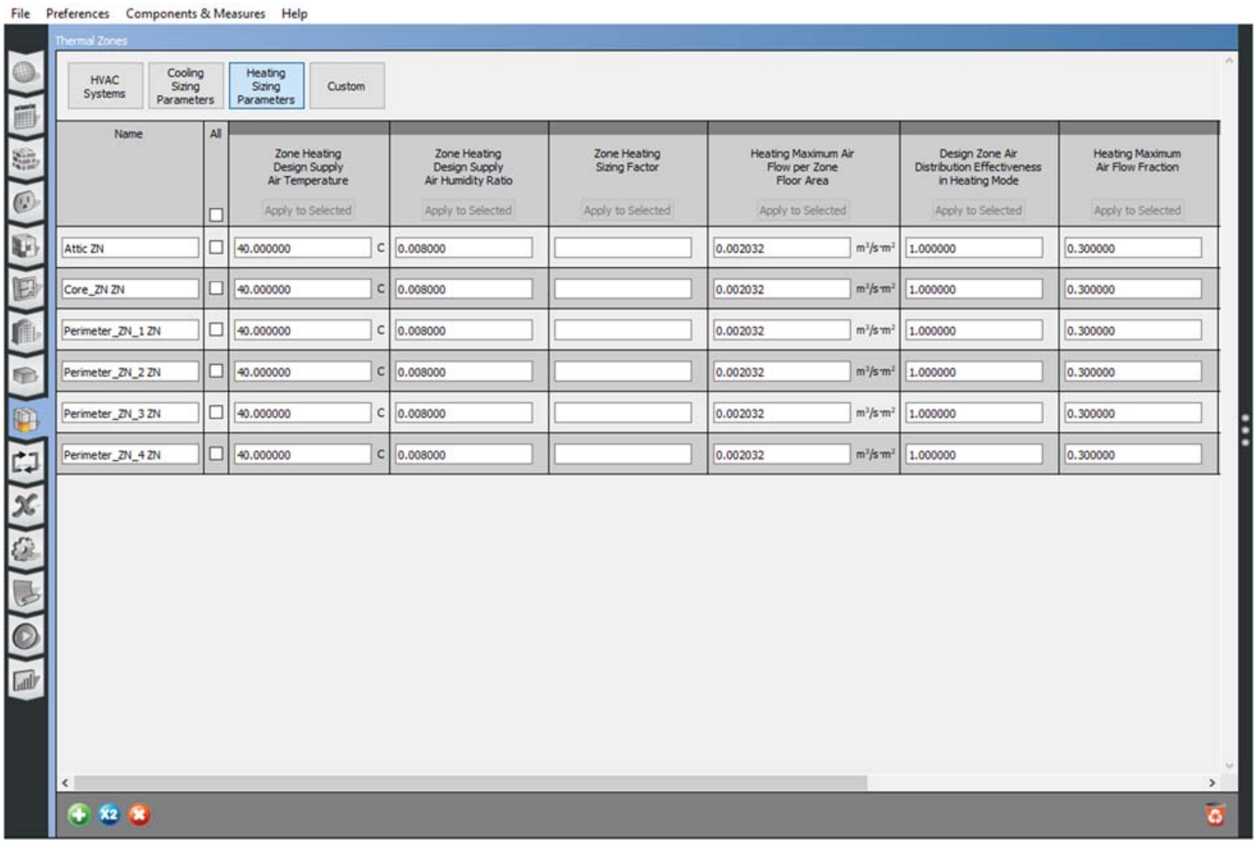


9. Thermal Zones

The thermal zones addressed the HVAC cooling and heating parameters. The HVAC was considered to only have one conditioned space setting for the entire building, name “single zone.” A plenum is an unconditioned space separate from the working space. This is usually the space above a drop ceiling where utilities are run while providing access for maintenance. The heating and cooling parameters shown below are typical HVAC values that might be seen in an office space for supply temperatures, humidity, flow rates, and air distribution.

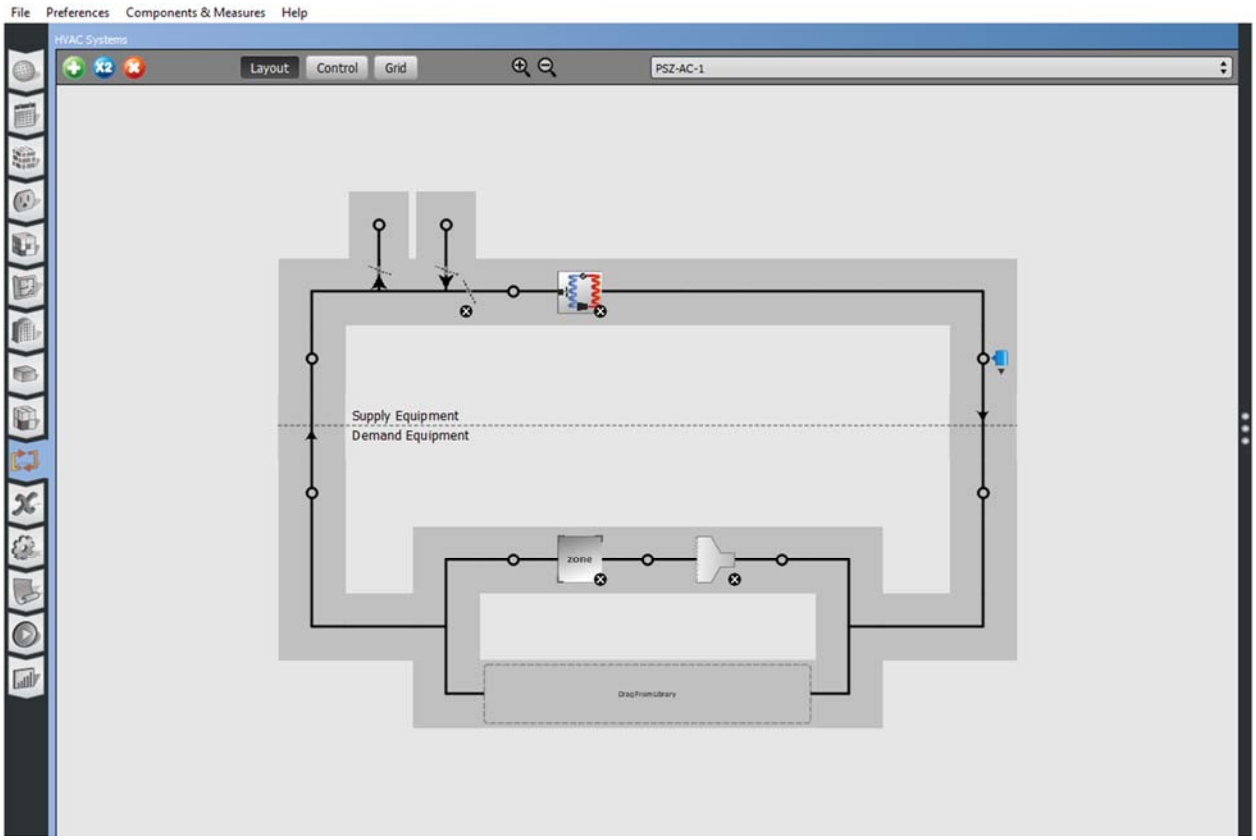

File
Preferences
Components & Measures
Help
Thermal Zones
HVAC Systems
Cooling Sizing Parameters
Heating Sizing Parameters
Custom
Name
All
Rendering Color
Turn On Ideal Air Loads
Air Loop Name
Zone Equipment
Cooling Thermostat Schedule
Heating Thermostat Schedule
Humidifying Setpoint Schedule
Apply to Selected
Attic ZN
Core_ZN ZN
Perimeter_ZN_1 ZN
Perimeter_ZN_2 ZN
Perimeter_ZN_3 ZN
Perimeter_ZN_4 ZN
PSZ-AC-1
PSZ-AC-2
PSZ-AC-3
PSZ-AC-4
PSZ-AC-5
PSZ-AC-1 Diffuser
PSZ-AC-2 Diffuser
PSZ-AC-3 Diffuser
PSZ-AC-4 Diffuser
PSZ-AC-5 Diffuser
OfficeSmall CLGSETP_SCH_N
OfficeSmall HTGSETP_SCH_N


File
Preferences
Components & Measures
Help
Thermal Zones
HVAC Systems
Cooling Sizing Parameters
Heating Sizing Parameters
Custom
Name
All
Zone Cooling Design Supply Air Temperature
Zone Cooling Design Supply Air Humidity Ratio
Zone Cooling Sizing Factor
Cooling Minimum Air Flow per Zone Floor Area
Design Zone Air Distribution Effectiveness in Cooling Mode
Cooling Minimum Air Flow Fraction
Apply to Selected
Attic ZN
Core_ZN ZN
Perimeter_ZN_1 ZN
Perimeter_ZN_2 ZN
Perimeter_ZN_3 ZN
Perimeter_ZN_4 ZN
14.000000
12.800000
C
0.008500
0.000762
m³/s·m²
1.000000
0.000000



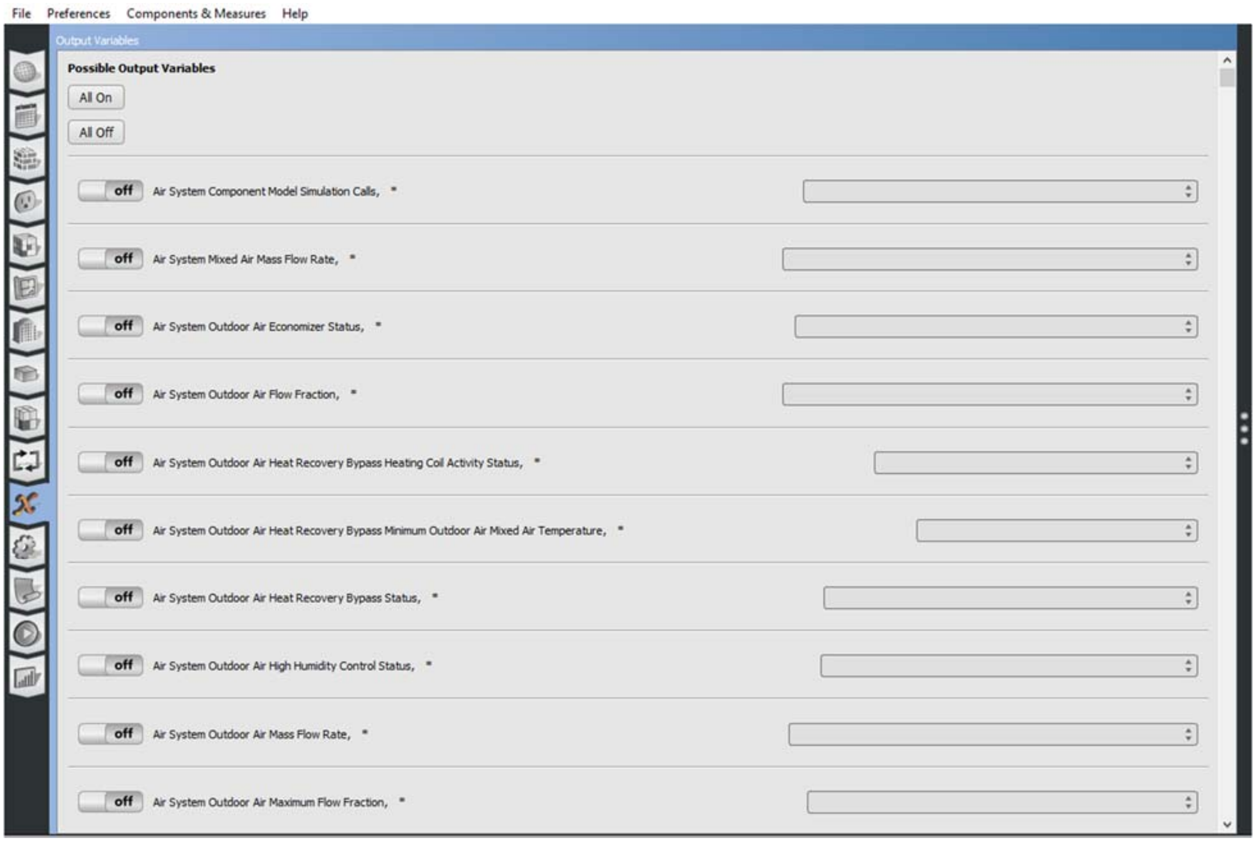
10. HVAC Systems

The HVAC system is modeled using a typical HVAC system model used in buildings. This building is modeled using a centralized, packaged unit with heating and cooling coils to condition supply air through ducts to the zones designated for conditioning. The return diffuser pulls air out of the zone and expels it outside or mixes it with fresh air to be used again as a supply.



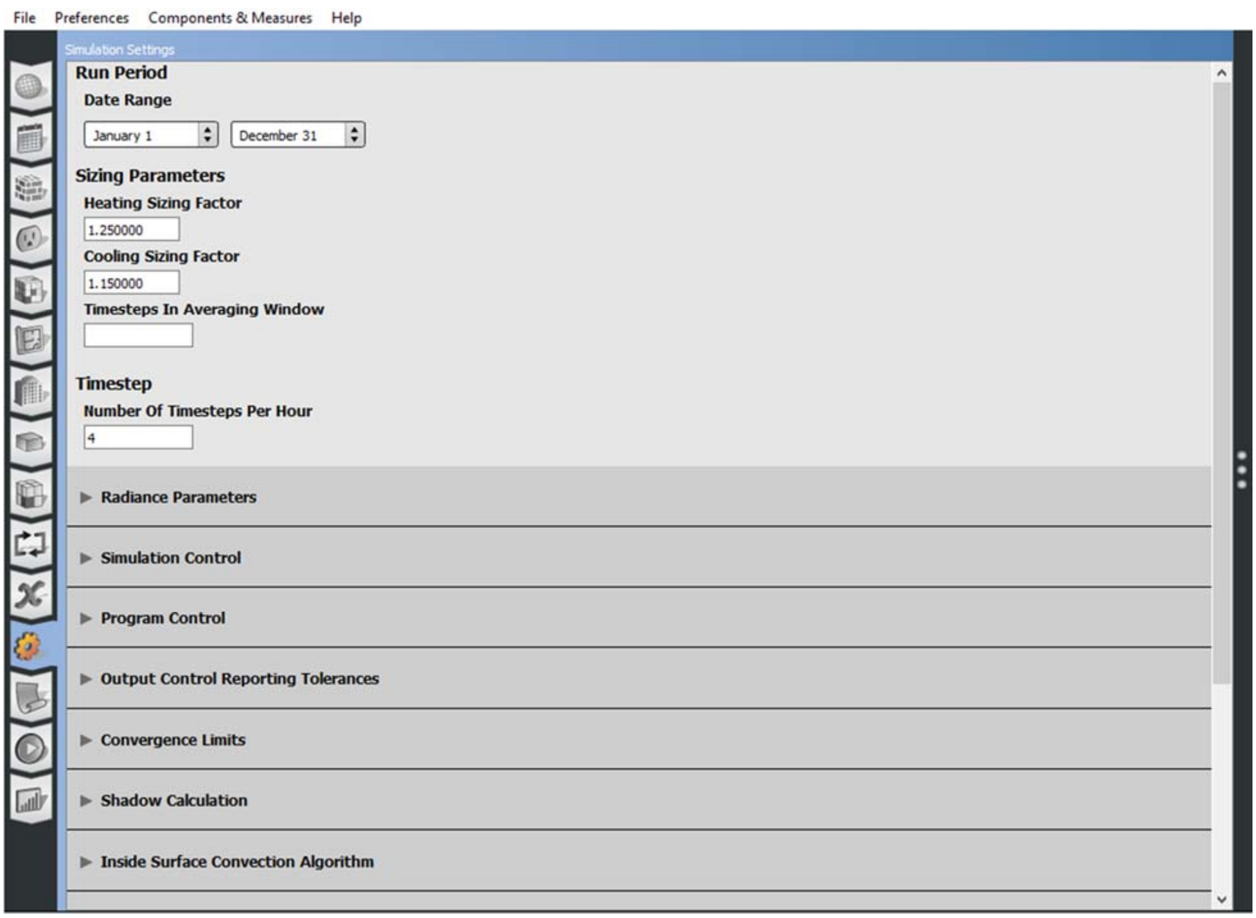
11. Output Variables

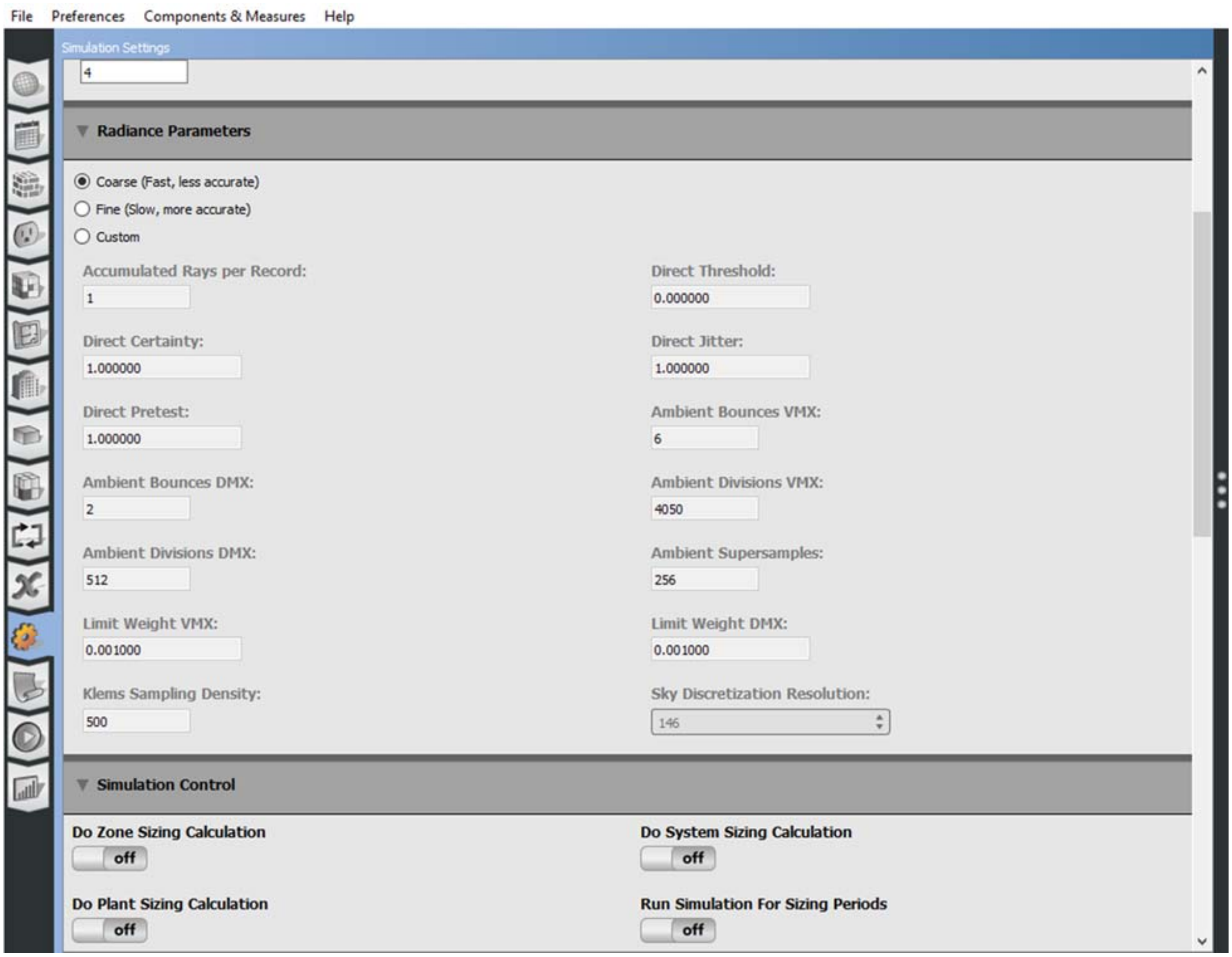
There are 571 possible output variables. All output variables remained ‘on’ except for 25 that were turned ‘off.’ All 25 had to do with HVAC zoning which was not used for this modeling.

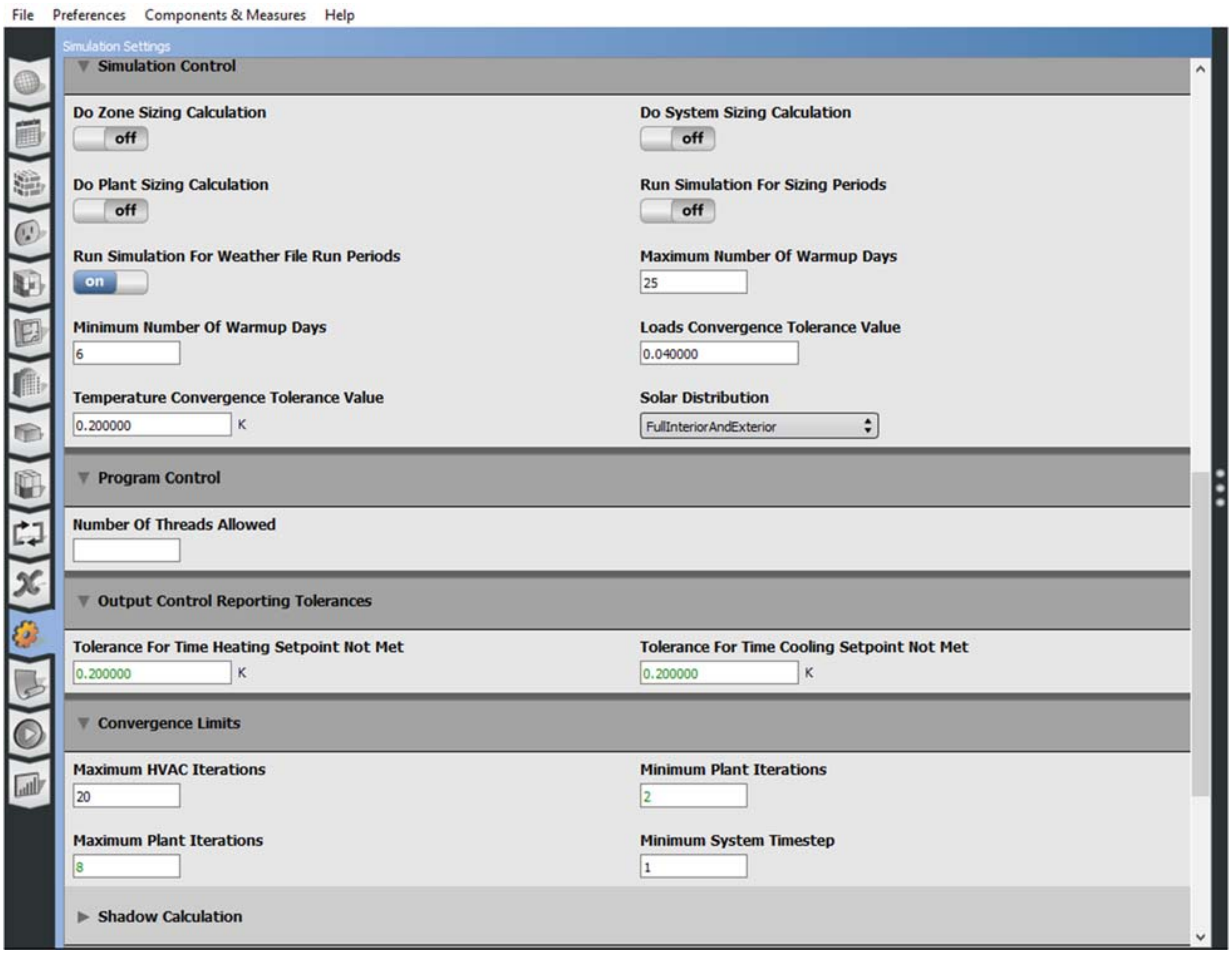


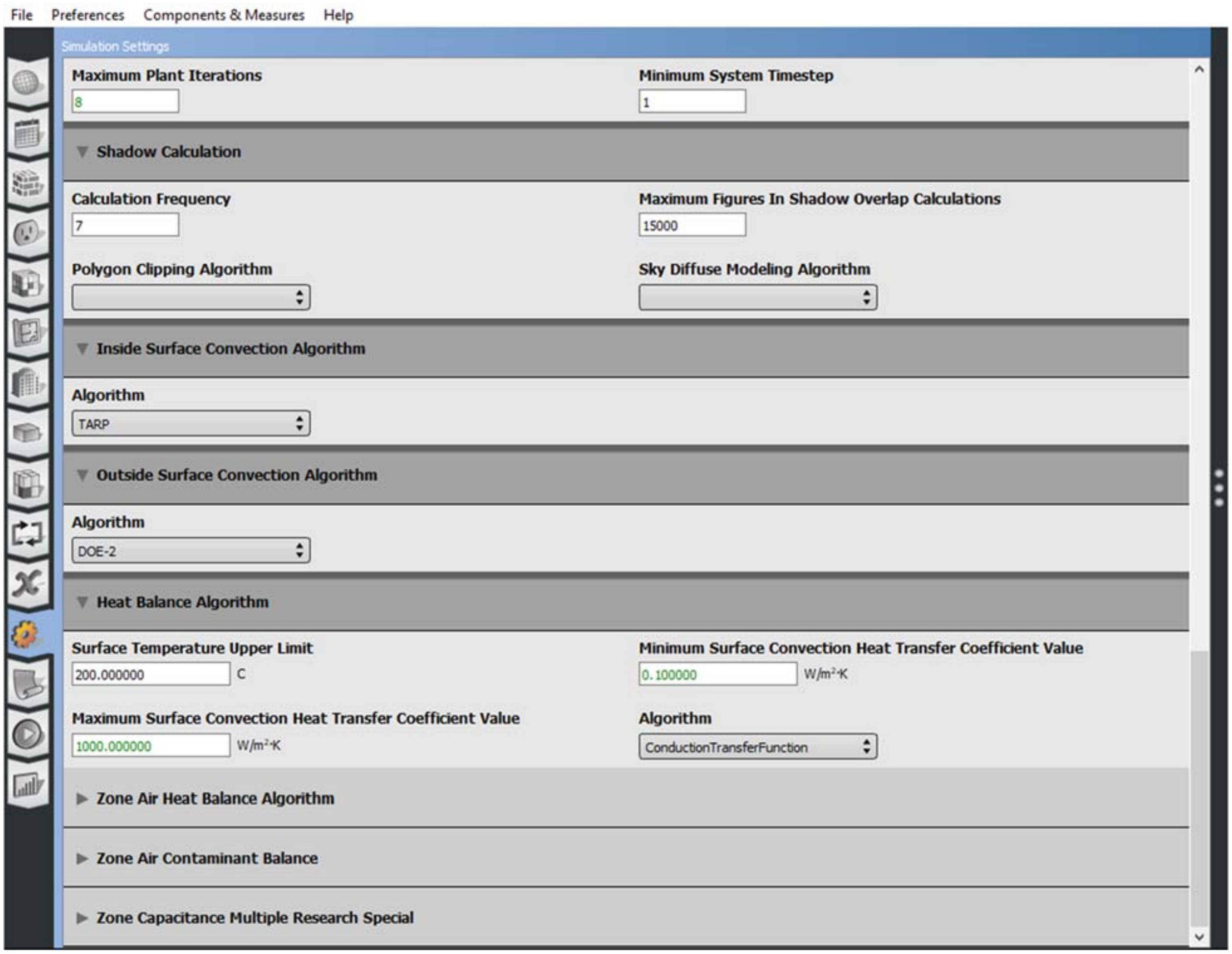
12. Simulation Settings

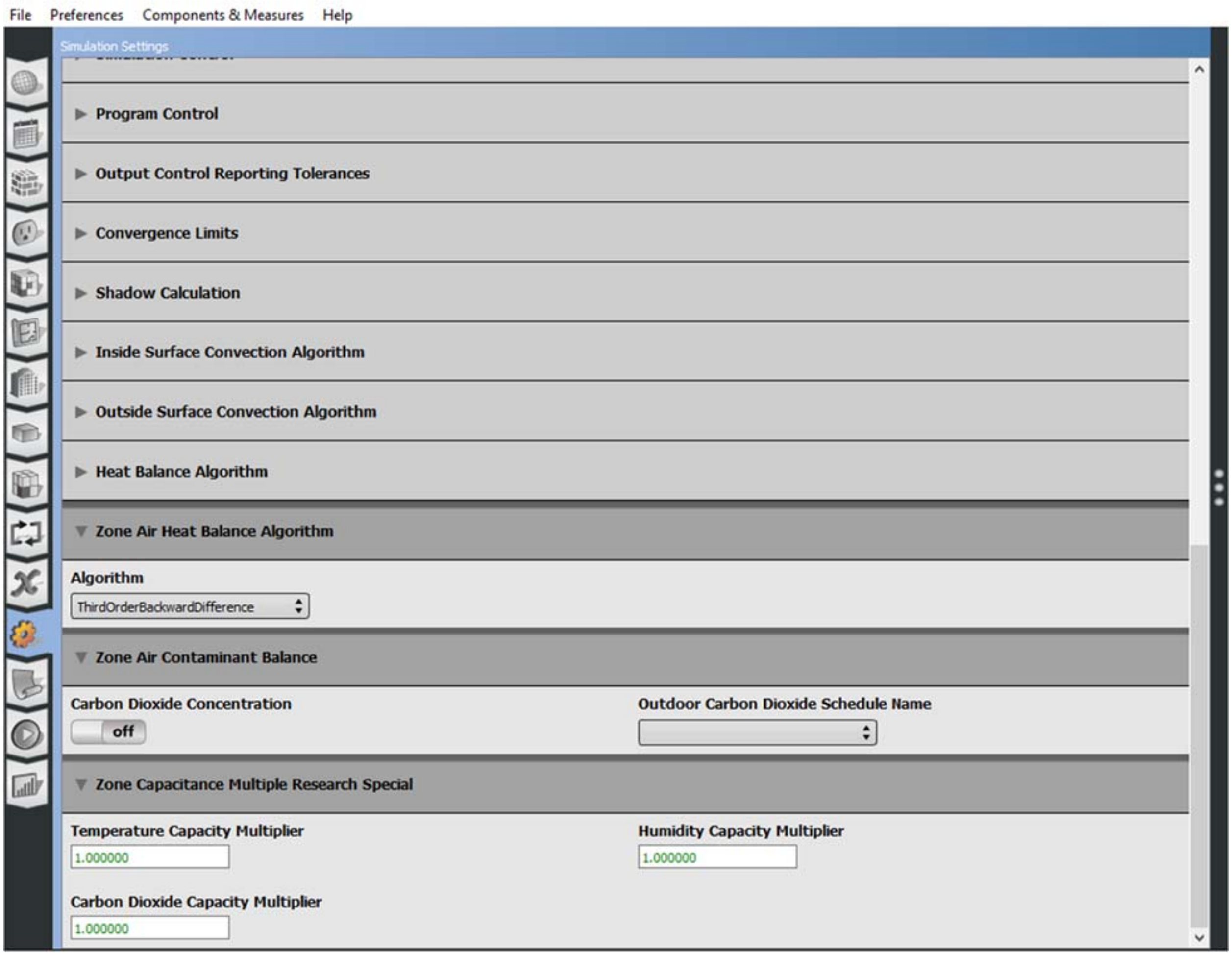
Below are the simulation settings used for this model. The sizing factor addresses the situation where an HVAC unit needs to be sized greater than the maximum design load provided by weather data. If an HVAC was sized exactly to the 'worst-case' design day, then it would fail to meet the demand. The other settings describe the parameters for the simulation algorithm to train, iterate, and converge. Many of these settings were carried over from the Open Studio tutorial ReadMe and example files.


File
Preferences
Components & Measures
Help
Simulation Settings
Run Period
Date Range
January 1
December 31
Sizing Parameters
Heating Sizing Factor
1.250000
Cooling Sizing Factor
1.150000
Timesteps In Averaging Window
Timestep
Number Of Timesteps Per Hour
4
Radiance Parameters
Simulation Control
Program Control
Output Control Reporting Tolerances
Convergence Limits
Shadow Calculation
Inside Surface Convection Algorithm


File
Preferences
Components & Measures
Help
Simulation Settings
4
Radiance Parameters
Coarse (Fast, less accurate)
Fine (Slow, more accurate)
Custom
Accumulated Rays per Record:
1
Direct Threshold:
0.000000
Direct Certainty:
1.000000
Direct Jitter:
1.000000
Direct Pretest:
1.000000
Ambient Bounces VMX:
6
Ambient Bounces DMX:
2
Ambient Divisions VMX:
4050
Ambient Divisions DMX:
512
Ambient Supersamples:
256
Limit Weight VMX:
0.001000
Limit Weight DMX:
0.001000
Klems Sampling Density:
500
Sky Discretization Resolution:
146
Simulation Control
Do Zone Sizing Calculation
off
Do System Sizing Calculation
off
Do Plant Sizing Calculation
off
Run Simulation For Sizing Periods
off


File
Preferences
Components & Measures
Help
Simulation Settings
Simulation Control
Do Zone Sizing Calculation
off
Do System Sizing Calculation
off
Do Plant Sizing Calculation
off
Run Simulation For Sizing Periods
off
Run Simulation For Weather File Run Periods
on
Maximum Number Of Warmup Days
25
Minimum Number Of Warmup Days
6
Loads Convergence Tolerance Value
0.040000
Temperature Convergence Tolerance Value
0.200000
K
Solar Distribution
FullInteriorAndExterior
Program Control
Number Of Threads Allowed
Output Control Reporting Tolerances
Tolerance For Time Heating Setpoint Not Met
0.200000
K
Tolerance For Time Cooling Setpoint Not Met
0.200000
K
Convergence Limits
Maximum HVAC Iterations
20
Minimum Plant Iterations
2
Maximum Plant Iterations
8
Minimum System Timestep
1
Shadow Calculation


File Preferences Components & Measures Help
Simulation Settings
Maximum Plant Iterations
8
Minimum System Timestep
1
Shadow Calculation
Calculation Frequency
7
Maximum Figures In Shadow Overlap Calculations
15000
Polygon Clipping Algorithm
Sky Diffuse Modeling Algorithm
Inside Surface Convection Algorithm
Algorithm
TARP
Outside Surface Convection Algorithm
Algorithm
DOE-2
Heat Balance Algorithm
Surface Temperature Upper Limit
200.000000
C
Minimum Surface Convection Heat Transfer Coefficient Value
0.100000
W/m²-K
Maximum Surface Convection Heat Transfer Coefficient Value
1000.000000
W/m²-K
Algorithm
ConductionTransferFunction
Zone Air Heat Balance Algorithm
Zone Air Contaminant Balance
Zone Capacitance Multiple Research Special

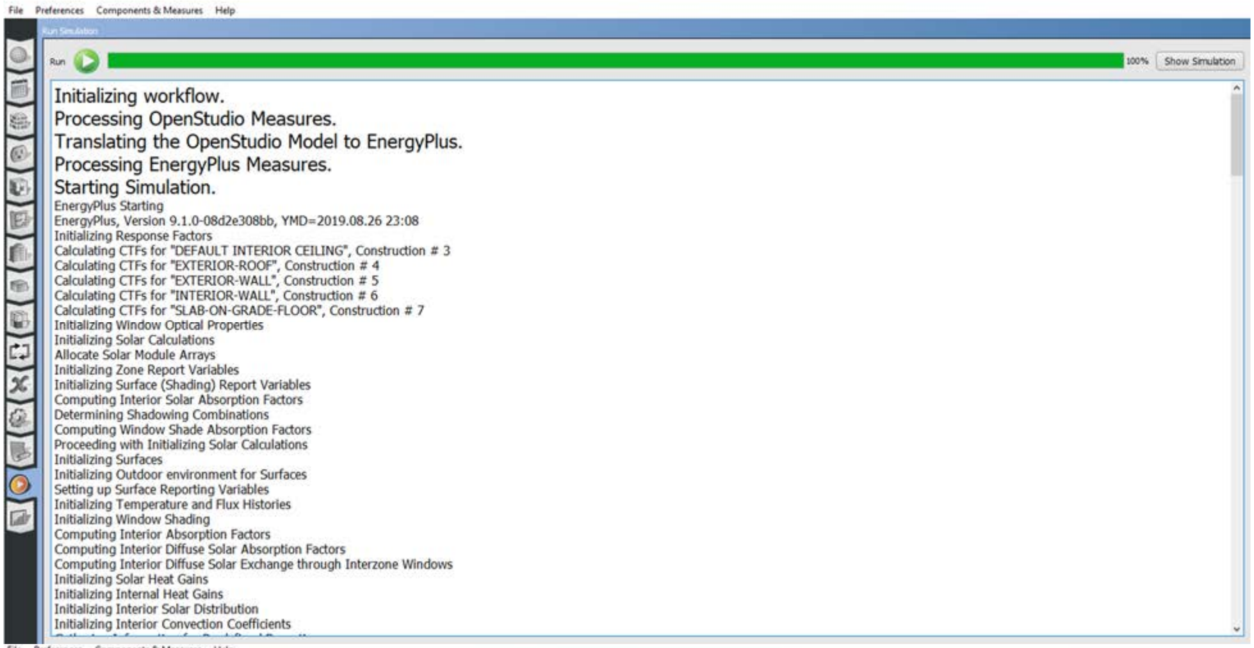


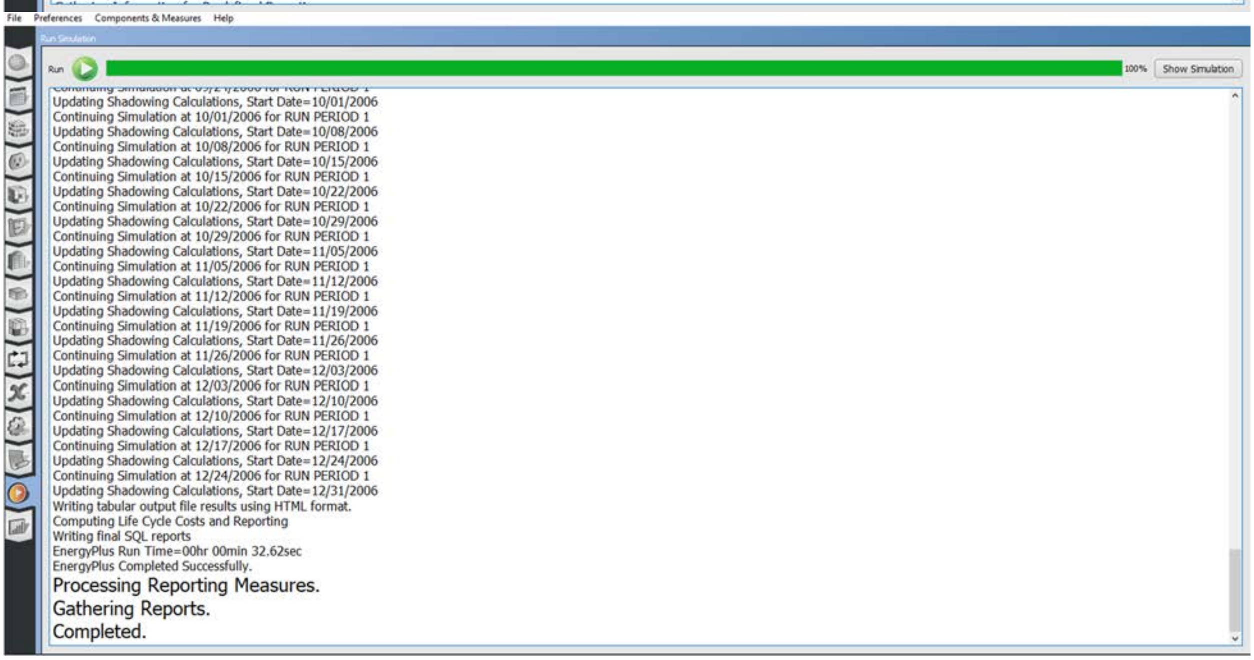
13. Measures

This section was not used for the simulation.

14. Run Simulation

This section runs the simulation once the ‘run’ button is pressed. The simulation inputs all the variables, parameters, and settings then it converts the model into Energy Plus and runs the algorithm and DOE modeling engine. Below the top and bottom of the simulation section is shown after the ‘run’ button is successfully pushed.





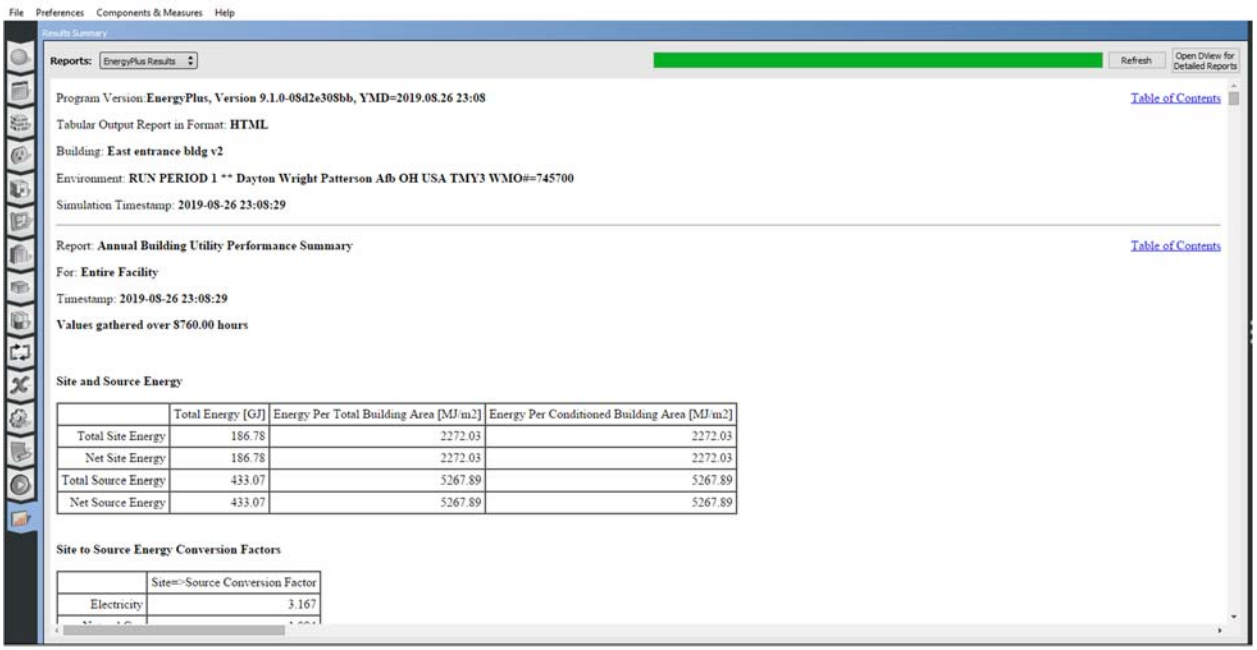
15. Results Summary

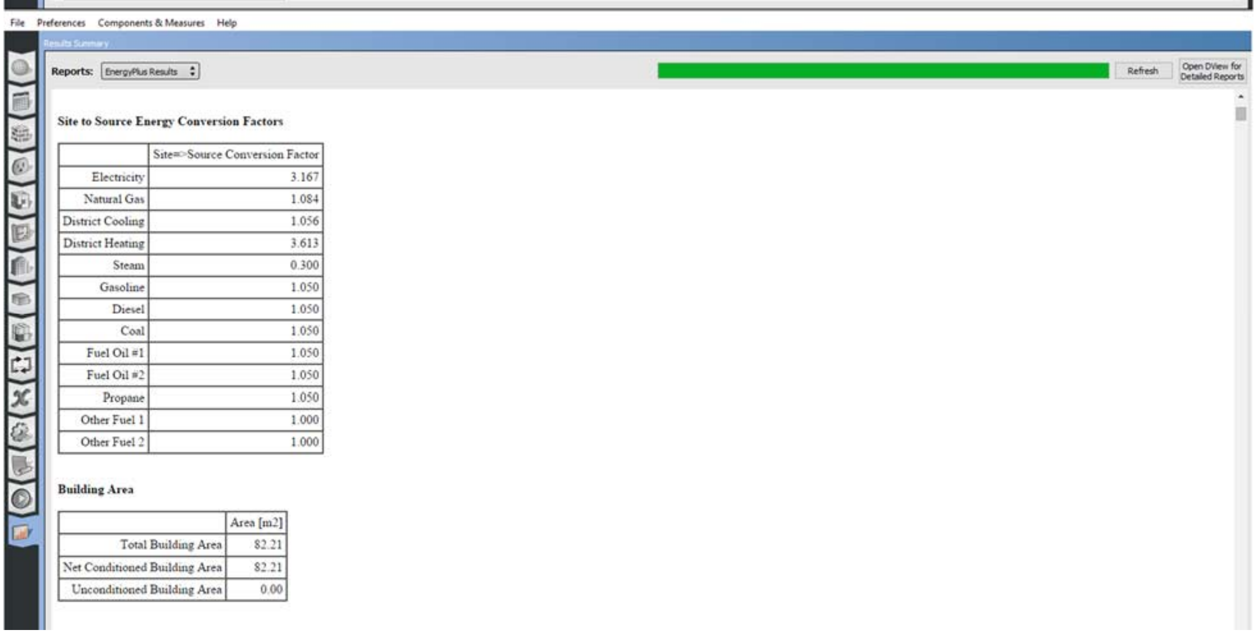
The results section provides the reports from the Energy Plus simulation. There are numerous different results that can be used for a multitude of applications beyond the function for this thesis. This research is primarily concerned with the total annual energy required to maintain a constant internal temperature. The 'total site energy' (GJ) provides the value for the total energy required for the building to maintain a constant temperature throughout the entire year.

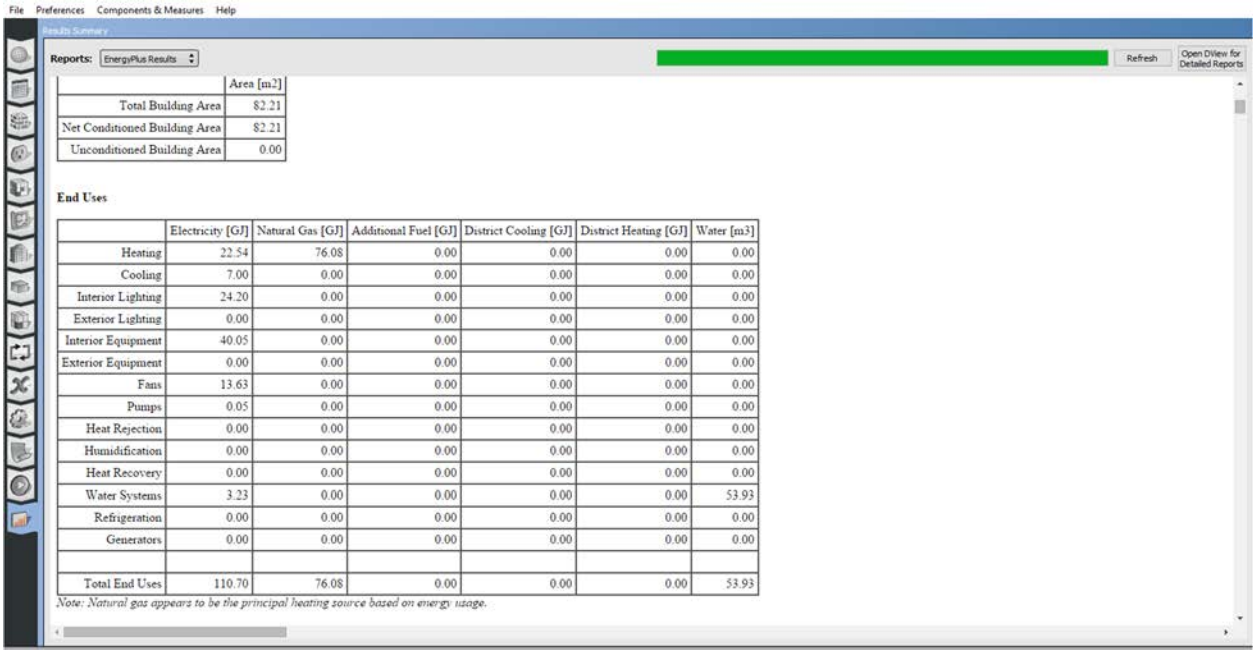
The second figure provides the source to site energy conversion factors. This is relevant to a life-cycle cost analysis whose boundary conditions are not limited to the facility. However, this research only looks at the life-cycle cost from the perspective of the building user or the Air Force, not the overall energy impact to the environment.

The third figure provides the subcategories for the building energy use. This is important because heating often uses natural gas which has a significantly different cost than electricity. The natural gas and electrical utility rates can be multiplied with the annual energy consumption to provide an annual cost. This will allow the simulation output to provide the annual energy sustainment cost. This annual sustainment cost may then be included in a total cost that includes acquisition costs, or the cost of construction. If the construction materials are varied, the total life-cycle cost may be compared.

Example Simulation output: (1) 186.78 GJ of total annual energy, (2) 76.08 GJ of annual natural gas energy, (3) 110.70 GJ of annual electrical energy.







	Area [m2]
Total Building Area	82.21
Net Conditioned Building Area	82.21
Unconditioned Building Area	0.00

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Additional Fuel [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	22.54	76.08	0.00	0.00	0.00	0.00
Cooling	7.00	0.00	0.00	0.00	0.00	0.00
Interior Lighting	24.20	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	40.05	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	13.63	0.00	0.00	0.00	0.00	0.00
Pumps	0.05	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	3.23	0.00	0.00	0.00	0.00	53.93
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	110.70	76.08	0.00	0.00	0.00	53.93

Note: Natural gas appears to be the principal heating source based on energy usage.

Simulation: Large prototypical USAF office building at WPAFB Dayton, OH

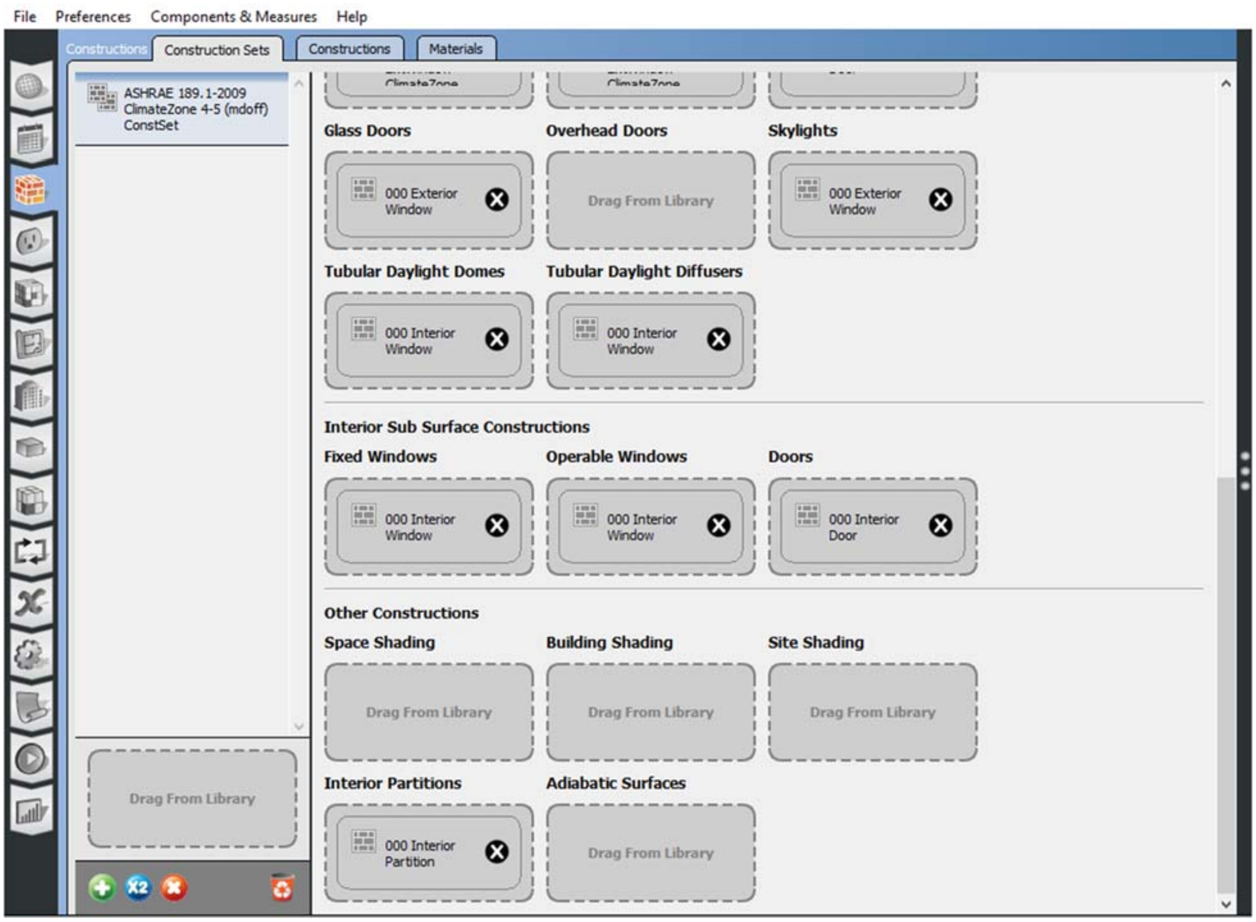
Energy Plus Simulation using Open Studio

Below are the screenshots for the sections in OpenStudio which were different for the large prototypical building.

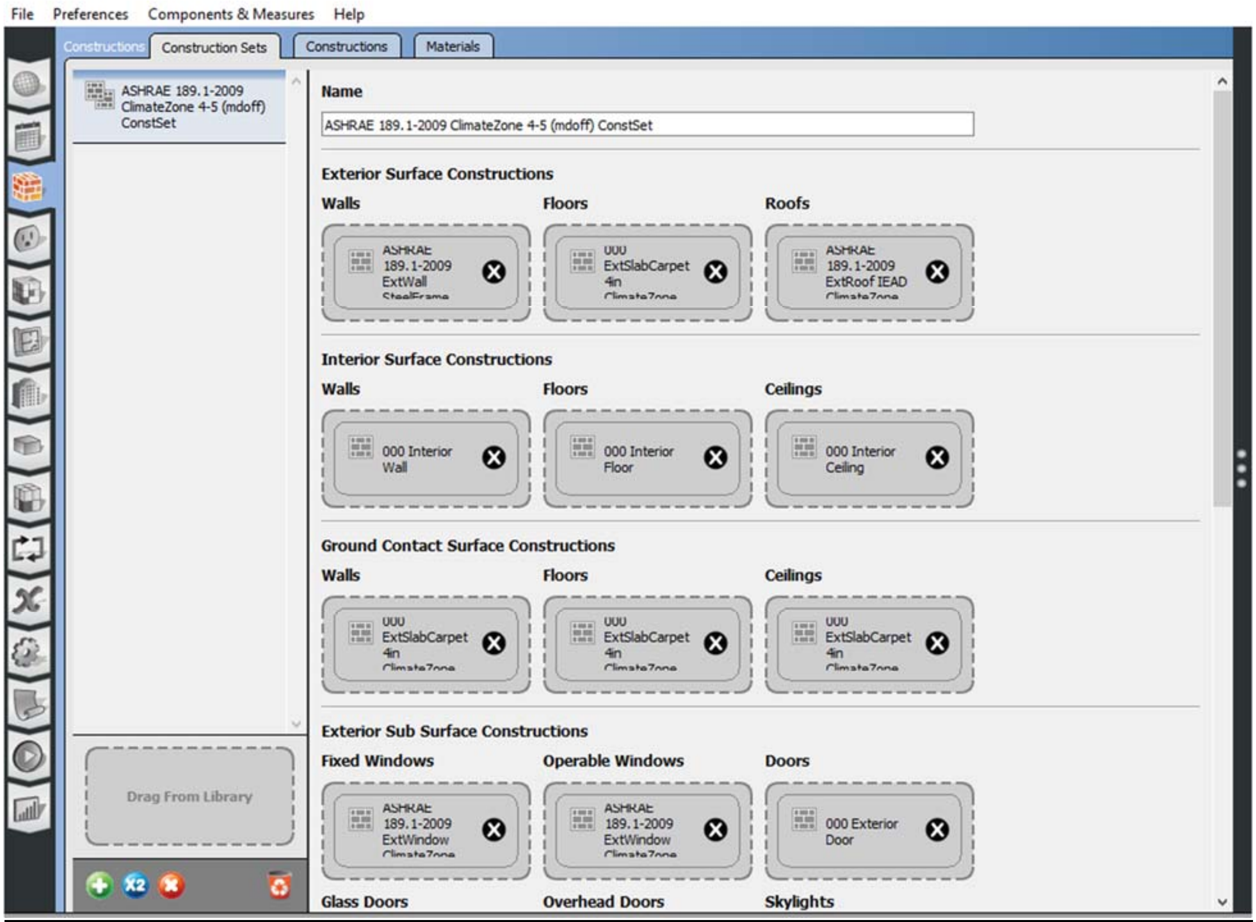
3. Constructions

a. Construction sets

The construction geometry of the large building is different than the small prototypical building requiring different construction shape, size, materials, and construction methods to be used. These construction material differences and properties are captured in section 3 of OpenStudio.

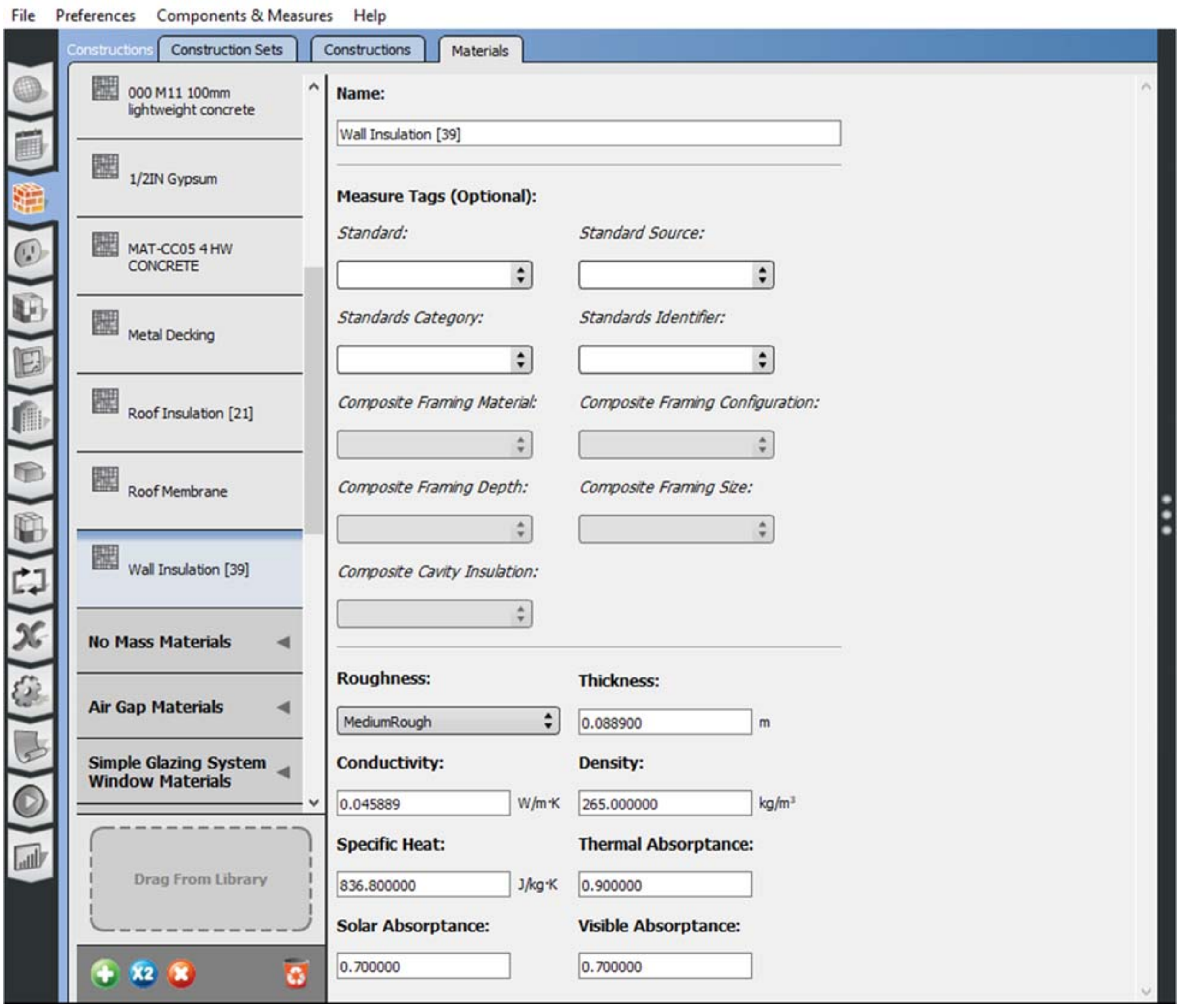


File
Preferences
Components & Measures
Help
Constructions
Construction Sets
Constructions
Materials
ASHRAE 189.1-2009 ClimateZone 4-5 (mdoff) ConstSet
Glass Doors
Overhead Doors
Skylights
000 Exterior Window
Drag From Library
000 Exterior Window
Tubular Daylight Domes
Tubular Daylight Diffusers
000 Interior Window
000 Interior Window
Interior Sub Surface Constructions
Fixed Windows
Operable Windows
Doors
000 Interior Window
000 Interior Window
000 Interior Door
Other Constructions
Space Shading
Building Shading
Site Shading
Drag From Library
Drag From Library
Drag From Library
Interior Partitions
Adiabatic Surfaces
000 Interior Partition
Drag From Library
Drag From Library



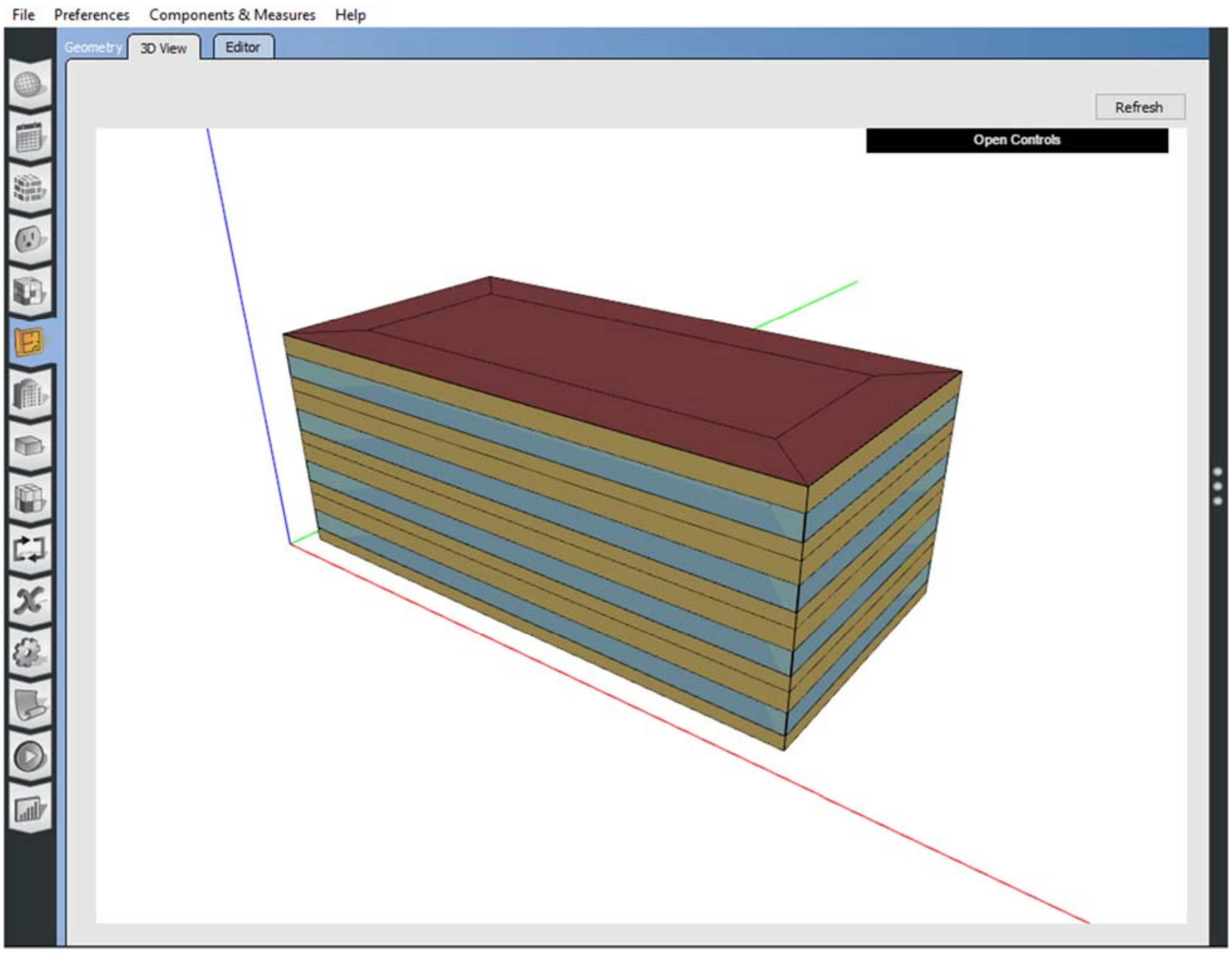
c. Materials

The large facility uses the material property conductivity to determine the insulation material's properties. The below figure shows an example of the material properties for R-11 wall insulation.

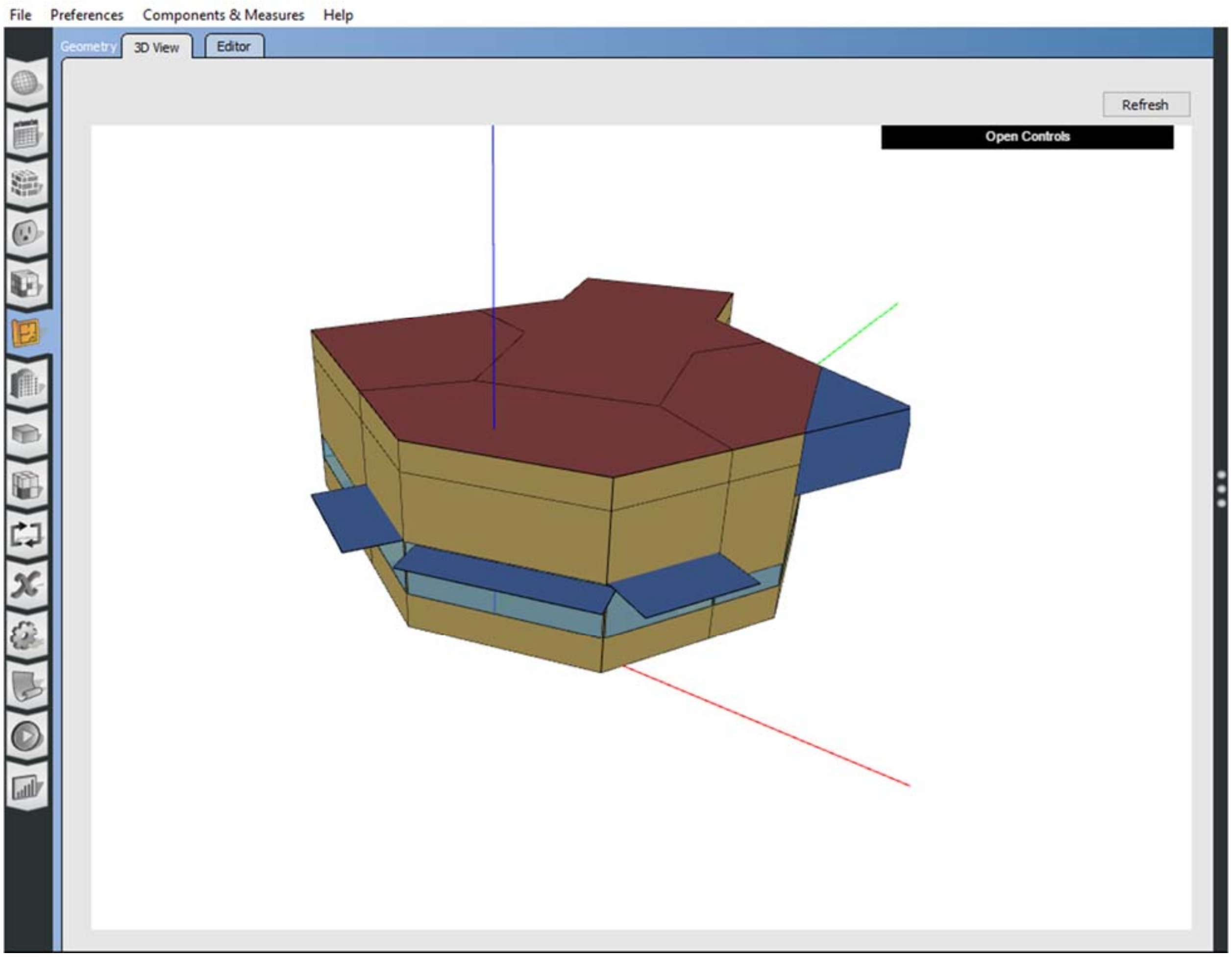


6. Geometry

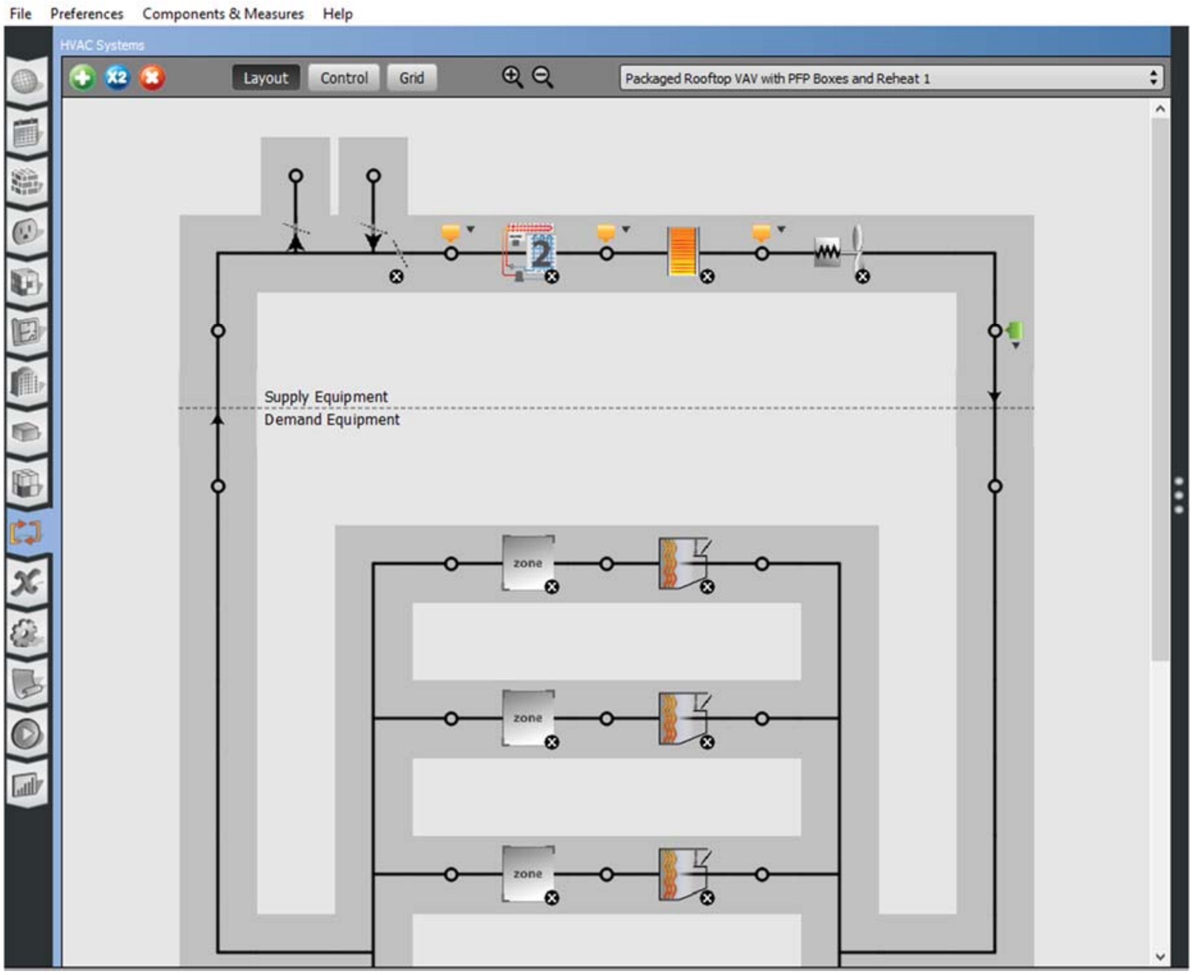
Below is the geometry used for the large prototypical building developed by PNNL.



Below is geometry used for the pilot study to test the capabilities of all the BPS software prior to selecting the BPS for this research.



10. HVAC Systems


File
Preferences
Components & Measures
Help
HVAC Systems
Layout
Control
Grid
Packaged Rooftop VAV with PFP Boxes and Reheat 1
Supply Equipment
Demand Equipment
zone
zone
zone

Appendix C: Annual Energy Cost Based on BPS Simulations

The following tables provide the total energy output from the OpenStudio simulation and the calculations to convert energy into cost.

WPAFB, OH		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	244.46	234.38	10.08	10.26	6.77	$ 6,967.11	$ 646.78
Insulation 2	Wall: R-13 Roof: R-30	243.09	233.52	9.57	10.26	6.77	$ 6,928.07	$ 614.05
Insulation 3	Wall: R-15 Roof: R-30	242.07	232.86	9.21	10.26	6.77	$ 6,899.00	$ 590.96
Insulation 4	Wall: R-21 Roof: R-30	240.15	231.64	8.51	10.26	6.77	$ 6,844.28	$ 546.04
Insulation 5	Wall: R-11 Roof: R-38	242.66	233.27	9.39	10.26	6.77	$ 6,915.81	$ 602.50
Insulation 6	Wall: R-13 Roof: R-38	241.29	232.41	8.88	10.26	6.77	$ 6,876.77	$ 569.78
Insulation 7	Wall: R-15 Roof: R-38	240.33	231.8	8.53	10.26	6.77	$ 6,849.41	$ 547.32
Insulation 8	Wall: R-21 Roof: R-38	238.58	230.65	7.93	10.26	6.77	$ 6,799.53	$ 508.82
Insulation 9	Wall: R-11 Roof: R-49	241.04	232.28	8.76	10.26	6.77	$ 6,869.64	$ 562.08
Insulation 10	Wall: R-13 Roof: R-49	239.83	231.5	8.33	10.26	6.77	$ 6,835.16	$ 534.49
Insulation 11	Wall: R-15 Roof: R-49	238.9	230.91	7.99	10.26	6.77	$ 6,808.65	$ 512.67
Insulation 12	Wall: R-21 Roof: R-49	237.31	229.83	7.48	10.26	6.77	$ 6,763.34	$ 479.95
Insulation 13	Wall: R-11 Roof: R-60	240.06	231.68	8.38	10.26	6.77	$ 6,841.71	$ 537.70
Insulation 14	Wall: R-13 Roof: R-60	238.92	230.93	7.99	10.26	6.77	$ 6,809.22	$ 512.67
Insulation 15	Wall: R-15 Roof: R-60	238.09	230.37	7.71	10.26	6.77	$ 6,785.57	$ 494.71
Insulation 16	Wall: R-21 Roof: R-60	236.46	229.28	7.18	10.26	6.77	$ 6,739.11	$ 460.70

WPAFB, OH		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Large Building	20000 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	1097.41	1097.41	0	10.26	6.77	$ 31,276.19	$ -
Insulation 2	Wall: R-13 Roof: R-30	1091.75	1091.75	0	10.26	6.77	$ 31,114.88	$ -
Insulation 3	Wall: R-15 Roof: R-30	1087.36	1087.36	0	10.26	6.77	$ 30,989.76	$ -
Insulation 4	Wall: R-21 Roof: R-30	1078.49	1078.49	0	10.26	6.77	$ 30,736.97	$ -
Insulation 5	Wall: R-11 Roof: R-38	1087.89	1087.89	0	10.26	6.77	$ 31,004.87	$ -
Insulation 6	Wall: R-13 Roof: R-38	1082.25	1082.25	0	10.26	6.77	$ 30,844.13	$ -
Insulation 7	Wall: R-15 Roof: R-38	1077.88	1077.88	0	10.26	6.77	$ 30,719.58	$ -
Insulation 8	Wall: R-21 Roof: R-38	1069.07	1069.07	0	10.26	6.77	$ 30,468.50	$ -
Insulation 9	Wall: R-11 Roof: R-49	1079.82	1079.82	0	10.26	6.77	$ 30,774.87	$ -
Insulation 10	Wall: R-13 Roof: R-49	1074.23	1074.23	0	10.26	6.77	$ 30,615.56	$ -
Insulation 11	Wall: R-15 Roof: R-49	1069.88	1069.88	0	10.26	6.77	$ 30,491.58	$ -
Insulation 12	Wall: R-21 Roof: R-49	1061.12	1061.12	0	10.26	6.77	$ 30,241.92	$ -
Insulation 13	Wall: R-11 Roof: R-60	1074.81	1074.81	0	10.26	6.77	$ 30,632.09	$ -
Insulation 14	Wall: R-13 Roof: R-60	1069.23	1069.23	0	10.26	6.77	$ 30,473.06	$ -
Insulation 15	Wall: R-15 Roof: R-60	1064.9	1064.9	0	10.26	6.77	$ 30,349.65	$ -
Insulation 16	Wall: R-21 Roof: R-60	1056.18	1056.18	0	10.26	6.77	$ 30,101.13	$ -

Langley, VA		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	235.08	233.29	1.79	11.84	9.18	$ 7,731.52	$ 155.74
Insulation 2	Wall: R-13 Roof: R-30	234.38	232.67	1.7	11.84	9.18	$ 7,708.50	$ 147.91
Insulation 3	Wall: R-15 Roof: R-30	233.89	232.23	1.66	11.84	9.18	$ 7,692.38	$ 144.43
Insulation 4	Wall: R-21 Roof: R-30	232.86	231.33	1.53	11.84	9.18	$ 7,658.51	$ 133.12
Insulation 5	Wall: R-11 Roof: R-38	234.17	232.52	1.65	11.84	9.18	$ 7,701.59	$ 143.56
Insulation 6	Wall: R-13 Roof: R-38	233.52	231.94	1.58	11.84	9.18	$ 7,680.21	$ 137.47
Insulation 7	Wall: R-15 Roof: R-38	233	231.47	1.52	11.84	9.18	$ 7,663.11	$ 132.25
Insulation 8	Wall: R-21 Roof: R-38	232.01	230.61	1.41	11.84	9.18	$ 7,630.55	$ 122.68
Insulation 9	Wall: R-11 Roof: R-49	233.44	231.89	1.56	11.84	9.18	$ 7,677.58	$ 135.73
Insulation 10	Wall: R-13 Roof: R-49	232.79	231.3	1.49	11.84	9.18	$ 7,656.20	$ 129.64
Insulation 11	Wall: R-15 Roof: R-49	232.25	230.85	1.4	11.84	9.18	$ 7,638.44	$ 121.81
Insulation 12	Wall: R-21 Roof: R-49	231.23	229.96	1.26	11.84	9.18	$ 7,604.90	$ 109.63
Insulation 13	Wall: R-11 Roof: R-60	232.97	231.48	1.49	11.84	9.18	$ 7,662.12	$ 129.64
Insulation 14	Wall: R-13 Roof: R-60	232.29	230.89	1.4	11.84	9.18	$ 7,639.76	$ 121.81
Insulation 15	Wall: R-15 Roof: R-60	231.73	230.42	1.31	11.84	9.18	$ 7,621.34	$ 113.98
Insulation 16	Wall: R-21 Roof: R-60	230.7	229.54	1.17	11.84	9.18	$ 7,587.47	$ 101.80

Langley, VA		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Large Building	20000 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	1010.54	1010.54	0	11.84	9.18	$ 33,235.54	$ -
Insulation 2	Wall: R-13 Roof: R-30	1006.66	1006.66	0	11.84	9.18	$ 33,107.93	$ -
Insulation 3	Wall: R-15 Roof: R-30	1003.65	1003.65	0	11.84	9.18	$ 33,008.93	$ -
Insulation 4	Wall: R-21 Roof: R-30	997.6	997.6	0	11.84	9.18	$ 32,809.96	$ -
Insulation 5	Wall: R-11 Roof: R-38	1003.93	1003.93	0	11.84	9.18	$ 33,018.14	$ -
Insulation 6	Wall: R-13 Roof: R-38	1000.08	1000.08	0	11.84	9.18	$ 32,891.52	$ -
Insulation 7	Wall: R-15 Roof: R-38	997.09	997.09	0	11.84	9.18	$ 32,793.18	$ -
Insulation 8	Wall: R-21 Roof: R-38	991.13	991.13	0	11.84	9.18	$ 32,597.16	$ -
Insulation 9	Wall: R-11 Roof: R-49	998.43	998.43	0	11.84	9.18	$ 32,837.25	$ -
Insulation 10	Wall: R-13 Roof: R-49	994.61	994.61	0	11.84	9.18	$ 32,711.62	$ -
Insulation 11	Wall: R-15 Roof: R-49	991.66	991.66	0	11.84	9.18	$ 32,614.60	$ -
Insulation 12	Wall: R-21 Roof: R-49	985.77	985.77	0	11.84	9.18	$ 32,420.88	$ -
Insulation 13	Wall: R-11 Roof: R-60	995.05	995.05	0	11.84	9.18	$ 32,726.09	$ -
Insulation 14	Wall: R-13 Roof: R-60	991.24	991.24	0	11.84	9.18	$ 32,600.78	$ -
Insulation 15	Wall: R-15 Roof: R-60	988.34	988.34	0	11.84	9.18	$ 32,505.40	$ -
Insulation 16	Wall: R-21 Roof: R-60	982.49	982.49	0	11.84	9.18	$ 32,313.00	$ -

San Antonio, TX		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	245.46	245.32	0.14	7.81	7.05	$ 5,325.12	$ 9.35
Insulation 2	Wall: R-13 Roof: R-30	244.9	244.76	0.13	7.81	7.05	$ 5,312.97	$ 8.69
Insulation 3	Wall: R-15 Roof: R-30	244.47	244.34	0.13	7.81	7.05	$ 5,303.64	$ 8.69
Insulation 4	Wall: R-21 Roof: R-30	243.65	243.53	0.11	7.81	7.05	$ 5,285.85	$ 7.35
Insulation 5	Wall: R-11 Roof: R-38	244.83	244.71	0.13	7.81	7.05	$ 5,311.45	$ 8.69
Insulation 6	Wall: R-13 Roof: R-38	244.28	244.16	0.12	7.81	7.05	$ 5,299.52	$ 8.02
Insulation 7	Wall: R-15 Roof: R-38	243.86	243.74	0.11	7.81	7.05	$ 5,290.41	$ 7.35
Insulation 8	Wall: R-21 Roof: R-38	243.03	242.93	0.1	7.81	7.05	$ 5,272.40	$ 6.68
Insulation 9	Wall: R-11 Roof: R-49	244.28	244.16	0.12	7.81	7.05	$ 5,299.52	$ 8.02
Insulation 10	Wall: R-13 Roof: R-49	243.73	243.62	0.11	7.81	7.05	$ 5,287.59	$ 7.35
Insulation 11	Wall: R-15 Roof: R-49	243.3	243.2	0.11	7.81	7.05	$ 5,278.26	$ 7.35
Insulation 12	Wall: R-21 Roof: R-49	242.47	242.37	0.1	7.81	7.05	$ 5,260.25	$ 6.68
Insulation 13	Wall: R-11 Roof: R-60	243.92	243.81	0.11	7.81	7.05	$ 5,291.71	$ 7.35
Insulation 14	Wall: R-13 Roof: R-60	243.37	243.27	0.1	7.81	7.05	$ 5,279.78	$ 6.68
Insulation 15	Wall: R-15 Roof: R-60	242.95	242.85	0.1	7.81	7.05	$ 5,270.67	$ 6.68
Insulation 16	Wall: R-21 Roof: R-60	242.12	242.03	0.09	7.81	7.05	$ 5,252.66	$ 6.01

San Antonio, TX		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Large Building	20000 SF				cents/kW	$/thousand cuft		
Insulation 1	Wall: R-11 Roof: R-30	992.03	992.03	0	7.81	7.05	$ 21,521.54	$ -
Insulation 2	Wall: R-13 Roof: R-30	989.99	989.99	0	7.81	7.05	$ 21,477.28	$ -
Insulation 3	Wall: R-15 Roof: R-30	988.38	988.38	0	7.81	7.05	$ 21,442.36	$ -
Insulation 4	Wall: R-21 Roof: R-30	985.21	985.21	0	7.81	7.05	$ 21,373.58	$ -
Insulation 5	Wall: R-11 Roof: R-38	988.51	988.51	0	7.81	7.05	$ 21,445.18	$ -
Insulation 6	Wall: R-13 Roof: R-38	986.49	986.49	0	7.81	7.05	$ 21,401.35	$ -
Insulation 7	Wall: R-15 Roof: R-38	984.87	984.87	0	7.81	7.05	$ 21,366.21	$ -
Insulation 8	Wall: R-21 Roof: R-38	981.75	981.75	0	7.81	7.05	$ 21,298.52	$ -
Insulation 9	Wall: R-11 Roof: R-49	985.7	985.7	0	7.81	7.05	$ 21,384.21	$ -
Insulation 10	Wall: R-13 Roof: R-49	983.69	983.69	0	7.81	7.05	$ 21,340.61	$ -
Insulation 11	Wall: R-15 Roof: R-49	982.11	982.11	0	7.81	7.05	$ 21,306.33	$ -
Insulation 12	Wall: R-21 Roof: R-49	979.06	979.06	0	7.81	7.05	$ 21,240.16	$ -
Insulation 13	Wall: R-11 Roof: R-60	983.99	983.99	0	7.81	7.05	$ 21,347.12	$ -
Insulation 14	Wall: R-13 Roof: R-60	981.99	981.99	0	7.81	7.05	$ 21,303.73	$ -
Insulation 15	Wall: R-15 Roof: R-60	980.43	980.43	0	7.81	7.05	$ 21,269.88	$ -
Insulation 16	Wall: R-21 Roof: R-60	977.38	977.38	0	7.81	7.05	$ 21,203.72	$ -

Edwards AFB, CA		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 0	Wall: 3.4 Roof: 3.9	259.79	258.01	1.78	14.25	8.17	$ 10,283.35	$ 137.83
Insulation 1	Wall: R-11 Roof: R-30	231.24	231.03	0.21	14.25	8.17	$ 9,153.25	$ 16.26
Insulation 2	Wall: R-13 Roof: R-30	230.71	230.52	0.19	14.25	8.17	$ 9,132.27	$ 14.71
Insulation 3	Wall: R-15 Roof: R-30	230.31	230.13	0.18	14.25	8.17	$ 9,116.44	$ 13.94
Insulation 4	Wall: R-21 Roof: R-30	229.53	229.36	0.16	14.25	8.17	$ 9,085.56	$ 12.39
Insulation 5	Wall: R-11 Roof: R-38	230.71	230.52	0.19	14.25	8.17	$ 9,132.27	$ 14.71
Insulation 6	Wall: R-13 Roof: R-38	230.19	230.02	0.17	14.25	8.17	$ 9,111.69	$ 13.16
Insulation 7	Wall: R-15 Roof: R-38	229.79	229.63	0.16	14.25	8.17	$ 9,095.85	$ 12.39
Insulation 8	Wall: R-21 Roof: R-38	229.02	228.88	0.14	14.25	8.17	$ 9,065.38	$ 10.84
Insulation 9	Wall: R-11 Roof: R-49	230.26	230.09	0.17	14.25	8.17	$ 9,114.46	$ 13.16
Insulation 10	Wall: R-13 Roof: R-49	229.74	229.58	0.16	14.25	8.17	$ 9,093.88	$ 12.39
Insulation 11	Wall: R-15 Roof: R-49	229.34	229.20	0.15	14.25	8.17	$ 9,078.04	$ 11.62
Insulation 12	Wall: R-21 Roof: R-49	228.58	228.46	0.12	14.25	8.17	$ 9,047.96	$ 9.29
Insulation 13	Wall: R-11 Roof: R-60	229.97	229.81	0.16	14.25	8.17	$ 9,102.98	$ 12.39
Insulation 14	Wall: R-13 Roof: R-60	229.45	229.30	0.15	14.25	8.17	$ 9,082.40	$ 11.62
Insulation 15	Wall: R-15 Roof: R-60	229.06	228.92	0.13	14.25	8.17	$ 9,066.96	$ 10.07
Insulation 16	Wall: R-21 Roof: R-60	228.30	228.19	0.11	14.25	8.17	$ 9,036.88	$ 8.52

Edwards AFB, CA		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Large Building	20000 SF				cents/kW	$/thousand cuft		
Insulation 0	Wall: 3.4 Roof: 3.7	1068.22	1068.22	0.00	14.25	8.17	$ 42,283.71	$ -
Insulation 1	Wall: R-11 Roof: R-30	895.66	895.66	0.00	14.25	8.17	$ 35,453.21	$ -
Insulation 2	Wall: R-13 Roof: R-30	892.88	892.88	0.00	14.25	8.17	$ 35,343.17	$ -
Insulation 3	Wall: R-15 Roof: R-30	890.74	890.74	0.00	14.25	8.17	$ 35,258.46	$ -
Insulation 4	Wall: R-21 Roof: R-30	886.54	886.54	0.00	14.25	8.17	$ 35,092.21	$ -
Insulation 5	Wall: R-11 Roof: R-38	891.23	891.23	0.00	14.25	8.17	$ 35,277.85	$ -
Insulation 6	Wall: R-13 Roof: R-38	888.52	888.52	0.00	14.25	8.17	$ 35,170.58	$ -
Insulation 7	Wall: R-15 Roof: R-38	886.44	886.44	0.00	14.25	8.17	$ 35,088.25	$ -
Insulation 8	Wall: R-21 Roof: R-38	882.34	882.34	0.00	14.25	8.17	$ 34,925.96	$ -
Insulation 9	Wall: R-11 Roof: R-49	887.96	887.96	0.00	14.25	8.17	$ 35,148.42	$ -
Insulation 10	Wall: R-13 Roof: R-49	885.30	885.30	0.00	14.25	8.17	$ 35,043.13	$ -
Insulation 11	Wall: R-15 Roof: R-49	883.24	883.24	0.00	14.25	8.17	$ 34,961.58	$ -
Insulation 12	Wall: R-21 Roof: R-49	879.22	879.22	0.00	14.25	8.17	$ 34,802.46	$ -
Insulation 13	Wall: R-11 Roof: R-60	886.10	886.10	0.00	14.25	8.17	$ 35,074.79	$ -
Insulation 14	Wall: R-13 Roof: R-60	883.45	883.45	0.00	14.25	8.17	$ 34,969.90	$ -
Insulation 15	Wall: R-15 Roof: R-60	881.44	881.44	0.00	14.25	8.17	$ 34,890.33	$ -
Insulation 16	Wall: R-21 Roof: R-60	877.46	877.46	0.00	14.25	8.17	$ 34,732.79	$ -

Ellsworth AFB, SD		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 0	Wall: 3.4 Roof: 3.9	447.57	348.88	98.69	10.21	6.76	$ 12,693.58	$ 6,323.04
Insulation 1	Wall: R-11 Roof: R-30	270.77	243.99	26.78	10.21	6.76	$ 7,679.34	$ 1,715.79
Insulation 2	Wall: R-13 Roof: R-30	268.32	242.66	25.67	10.21	6.76	$ 7,609.85	$ 1,644.67
Insulation 3	Wall: R-15 Roof: R-30	266.40	241.65	24.75	10.21	6.76	$ 7,555.40	$ 1,585.73
Insulation 4	Wall: R-21 Roof: R-30	262.89	239.74	23.15	10.21	6.76	$ 7,455.85	$ 1,483.21
Insulation 5	Wall: R-11 Roof: R-38	267.38	242.22	25.15	10.21	6.76	$ 7,583.19	$ 1,611.35
Insulation 6	Wall: R-13 Roof: R-38	265.05	240.95	24.11	10.21	6.76	$ 7,517.11	$ 1,544.72
Insulation 7	Wall: R-15 Roof: R-38	263.30	240.00	23.30	10.21	6.76	$ 7,467.48	$ 1,492.83
Insulation 8	Wall: R-21 Roof: R-38	259.96	238.10	21.77	10.21	6.76	$ 7,372.75	$ 1,394.80
Insulation 9	Wall: R-11 Roof: R-49	264.50	240.73	23.81	10.21	6.76	$ 7,501.51	$ 1,525.50
Insulation 10	Wall: R-13 Roof: R-49	262.30	239.49	22.81	10.21	6.76	$ 7,439.12	$ 1,461.43
Insulation 11	Wall: R-15 Roof: R-49	260.64	238.61	22.03	10.21	6.76	$ 7,392.04	$ 1,411.46
Insulation 12	Wall: R-21 Roof: R-49	257.36	236.82	20.55	10.21	6.76	$ 7,299.02	$ 1,316.63
Insulation 13	Wall: R-11 Roof: R-60	262.76	239.81	22.96	10.21	6.76	$ 7,452.17	$ 1,471.04
Insulation 14	Wall: R-13 Roof: R-60	260.61	238.64	21.97	10.21	6.76	$ 7,391.19	$ 1,407.61
Insulation 15	Wall: R-15 Roof: R-60	258.93	237.71	21.22	10.21	6.76	$ 7,343.54	$ 1,359.56
Insulation 16	Wall: R-21 Roof: R-60	255.81	235.98	19.83	10.21	6.76	$ 7,255.06	$ 1,270.50

Ellsworth AFB, SD		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Large Building	20000 SF				cents/kW	$/thousand cuft		
Insulation 0	Wall: 3.4 Roof: 3.7	1966.61	1966.61	0.00	10.21	6.76	$ 55,775.24	$ -
Insulation 1	Wall: R-11 Roof: R-30	1230.23	1230.23	0.00	10.21	6.76	$ 34,890.69	$ -
Insulation 2	Wall: R-13 Roof: R-30	1222.35	1222.35	0.00	10.21	6.76	$ 34,667.20	$ -
Insulation 3	Wall: R-15 Roof: R-30	1216.20	1216.20	0.00	10.21	6.76	$ 34,492.78	$ -
Insulation 4	Wall: R-21 Roof: R-30	1203.88	1203.88	0.00	10.21	6.76	$ 34,143.37	$ -
Insulation 5	Wall: R-11 Roof: R-38	1217.05	1217.05	0.00	10.21	6.76	$ 34,516.89	$ -
Insulation 6	Wall: R-13 Roof: R-38	1209.20	1209.20	0.00	10.21	6.76	$ 34,294.26	$ -
Insulation 7	Wall: R-15 Roof: R-38	1203.08	1203.08	0.00	10.21	6.76	$ 34,120.69	$ -
Insulation 8	Wall: R-21 Roof: R-38	1190.83	1190.83	0.00	10.21	6.76	$ 33,773.26	$ -
Insulation 9	Wall: R-11 Roof: R-49	1205.77	1205.77	0.00	10.21	6.76	$ 34,196.98	$ -
Insulation 10	Wall: R-13 Roof: R-49	1197.97	1197.97	0.00	10.21	6.76	$ 33,975.76	$ -
Insulation 11	Wall: R-15 Roof: R-49	1191.87	1191.87	0.00	10.21	6.76	$ 33,802.76	$ -
Insulation 12	Wall: R-21 Roof: R-49	1179.69	1179.69	0.00	10.21	6.76	$ 33,457.32	$ -
Insulation 13	Wall: R-11 Roof: R-60	1198.69	1198.69	0.00	10.21	6.76	$ 33,996.18	$ -
Insulation 14	Wall: R-13 Roof: R-60	1190.90	1190.90	0.00	10.21	6.76	$ 33,775.25	$ -
Insulation 15	Wall: R-15 Roof: R-60	1184.83	1184.83	0.00	10.21	6.76	$ 33,603.10	$ -
Insulation 16	Wall: R-21 Roof: R-60	1172.66	1172.66	0.00	10.21	6.76	$ 33,257.94	$ -

Minot AFB, ND		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Small Building	5500 SF				cents/kW	$/thousand cuft		
Insulation 0	Wall: 3.4 Roof: 3.9	383.32	282.09	101.23	10.21	6.76	$ 10,871.38	$ 6,485.78
Insulation 1	Wall: R-11 Roof: R-30	289.31	242.57	46.74	10.21	6.76	$ 8,205.15	$ 2,994.62
Insulation 2	Wall: R-13 Roof: R-30	286.63	241.47	45.16	10.21	6.76	$ 8,129.15	$ 2,893.39
Insulation 3	Wall: R-15 Roof: R-30	284.51	240.60	43.91	10.21	6.76	$ 8,069.02	$ 2,813.30
Insulation 4	Wall: R-21 Roof: R-30	280.28	238.87	41.40	10.21	6.76	$ 7,949.05	$ 2,652.49
Insulation 5	Wall: R-11 Roof: R-38	285.64	241.12	44.52	10.21	6.76	$ 8,101.07	$ 2,852.39
Insulation 6	Wall: R-13 Roof: R-38	282.91	240.04	42.87	10.21	6.76	$ 8,023.64	$ 2,746.67
Insulation 7	Wall: R-15 Roof: R-38	280.79	239.13	41.66	10.21	6.76	$ 7,963.52	$ 2,669.15
Insulation 8	Wall: R-21 Roof: R-38	276.41	237.39	39.02	10.21	6.76	$ 7,839.29	$ 2,500.00
Insulation 9	Wall: R-11 Roof: R-49	282.29	239.83	42.46	10.21	6.76	$ 8,006.06	$ 2,720.40
Insulation 10	Wall: R-13 Roof: R-49	279.48	238.66	40.82	10.21	6.76	$ 7,926.36	$ 2,615.33
Insulation 11	Wall: R-15 Roof: R-49	277.21	237.77	39.44	10.21	6.76	$ 7,861.98	$ 2,526.91
Insulation 12	Wall: R-21 Roof: R-49	273.09	236.08	37.00	10.21	6.76	$ 7,745.14	$ 2,370.58
Insulation 13	Wall: R-11 Roof: R-60	280.04	238.96	41.08	10.21	6.76	$ 7,942.25	$ 2,631.99
Insulation 14	Wall: R-13 Roof: R-60	277.19	237.82	39.37	10.21	6.76	$ 7,861.42	$ 2,522.43
Insulation 15	Wall: R-15 Roof: R-60	274.96	236.94	38.03	10.21	6.76	$ 7,798.17	$ 2,436.57
Insulation 16	Wall: R-21 Roof: R-60	270.96	235.27	35.69	10.21	6.76	$ 7,684.73	$ 2,286.65

Minot AFB, ND		Total Energy (GJ)	Electricity (GJ)	Nat Gas (GJ)	Electricity Rate	Nat Gas Rate	Annual Electricity Cost	Annual Nat Gas Cost
Large Building	20000 SF				cents/kW	$/thousand cuft		
Insulation 0	Wall: 3.4 Roof: 3.7	2181.14	2181.14	0.00	10.21	6.76	$ 61,859.55	$ -
Insulation 1	Wall: R-11 Roof: R-30	1339.78	1339.78	0.00	10.21	6.76	$ 37,997.65	$ -
Insulation 2	Wall: R-13 Roof: R-30	1330.77	1330.77	0.00	10.21	6.76	$ 37,742.12	$ -
Insulation 3	Wall: R-15 Roof: R-30	1323.75	1323.75	0.00	10.21	6.76	$ 37,543.02	$ -
Insulation 4	Wall: R-21 Roof: R-30	1309.64	1309.64	0.00	10.21	6.76	$ 37,142.85	$ -
Insulation 5	Wall: R-11 Roof: R-38	1324.80	1324.80	0.00	10.21	6.76	$ 37,572.80	$ -
Insulation 6	Wall: R-13 Roof: R-38	1315.83	1315.83	0.00	10.21	6.76	$ 37,318.40	$ -
Insulation 7	Wall: R-15 Roof: R-38	1308.80	1308.80	0.00	10.21	6.76	$ 37,119.02	$ -
Insulation 8	Wall: R-21 Roof: R-38	1294.76	1294.76	0.00	10.21	6.76	$ 36,720.83	$ -
Insulation 9	Wall: R-11 Roof: R-49	1311.93	1311.93	0.00	10.21	6.76	$ 37,207.79	$ -
Insulation 10	Wall: R-13 Roof: R-49	1302.98	1302.98	0.00	10.21	6.76	$ 36,953.96	$ -
Insulation 11	Wall: R-15 Roof: R-49	1295.99	1295.99	0.00	10.21	6.76	$ 36,755.72	$ -
Insulation 12	Wall: R-21 Roof: R-49	1282.00	1282.00	0.00	10.21	6.76	$ 36,358.94	$ -
Insulation 13	Wall: R-11 Roof: R-60	1303.80	1303.80	0.00	10.21	6.76	$ 36,977.22	$ -
Insulation 14	Wall: R-13 Roof: R-60	1294.87	1294.87	0.00	10.21	6.76	$ 36,723.95	$ -
Insulation 15	Wall: R-15 Roof: R-60	1287.91	1287.91	0.00	10.21	6.76	$ 36,526.56	$ -
Insulation 16	Wall: R-21 Roof: R-60	1273.95	1273.95	0.00	10.21	6.76	$ 36,130.64	$ -

Appendix D: Acquisition Cost Calculations

The following tables provide the acquisition cost calculations made using the RSMeans book 'Building Construction Costs with RSMeans Data.'

Calculations for Dayton, OH

Division 07: Thermal and Moisture Protection | Key: RS Means Data | Calculation | Adjustment Factor From City Cost Table

ID	Activity	Quantity	Unit	Daily Output	Duration (days)	Material ($/Unit)	Material Adj.	Material Cost	Crew	Labor ($/Unit)	Labor Adj. Factor	Labor Cost	Equip ($/Unit)	Equip Adj. Factor	Equip Cost	Total Cost	RSMeans Item Number
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000.0	SF	600	8.33	0.52	1.199	$ 3,117	1 Carp	0.66	1.127	$ 3,719	0	0.787	$ -	$ 6,836	07-21-16-10-2150
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"" thick, R30	5,000.0	SF	500	10.00	0.75	1.199	$ 4,495	1 Carp	0.79	1.127	$ 4,452	0	0.787	$ -	$ 8,947	07-21-16-10-2210
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000.0	SF	475	10.53	1.08	1.199	$ 6,473	1 Carp	0.83	1.127	$ 4,677	0	0.787	$ -	$ 11,150	07-21-16-10-2220
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"" thick, R30	5,000.0	SF	450	11.11	0.62	1.199	$ 3,716	1 Carp	0.88	1.127	$ 4,959	0	0.787	$ -	$ 8,675	07-21-16-10-3020
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040.0	SF	1350	5.96	0.32	1.199	$ 3,084	1 Carp	0.29	1.127	$ 2,628	0	0.787	$ -	$ 5,712	07-21-16-20-0020
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040.0	SF	1350	5.96	0.48	1.199	$ 4,626	1 Carp	0.29	1.127	$ 2,628	0	0.787	$ -	$ 7,254	07-21-16-20-0420
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040.0	SF	1350	5.96	0.5	1.199	$ 4,819	1 Carp	0.29	1.127	$ 2,628	0	0.787	$ -	$ 7,447	07-21-16-20-0444
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040.0	SF	1715	4.69	1.81	1.199	$ 17,444	G-2A	0.53	1.214	$ 5,173	0.39	0.787	$ 2,468	$ 25,085	07-21-29-10-0335

		$ 14,659
Overhead	10%	$ 1,466
Profit and Contingency	5%	$ 806
Total		$ 16,930.69

City Cost Table: Dayton, OH

Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	1.062	1.199	1.432	0.787	1.127	0.787
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	1.062	1.199	1.543	0.787	1.214	0.787

Labor Overhead and Labor Adjustment Factor Table

Crew		hour	daily	# Workers	B (From Table in Back Cover of RSMeans)	C	D	B + C + D	Workers x rate	Total Crew	sum (BCD) x work rate	Total Labor OH	Labor Overhead Total Labor OH / Total Crew
G-2A	1 Roofer Compositio	43.15	345.20	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.10	256.80	1	30.7	18.3	11	60.0	32.10		19.26		
	1 Buillding Laborer	39.15	313.20	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		**62.06**	0.543
1 Carp	1 Carpenter	49.25	394.00	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		**21.28**	0.432

Calculations for Newport News, VA

	Division 07: Thermal and Moisture Protection		Key:	RS Means Data	Calculation	Adjustment Factor From City Cost Table										
ID	**Activity**	**Quantity**	**Unit**	**Daily Output**	**Duration (days)**	**Material ($/Unit)**	**Material Adj.**	**Material Cost**	**Crew**	**Labor ($/Unit)**	**Labor Adj. Factor**	**Labor Cost**	**Equip ($/Unit)**	**Equip Adj. Factor**	**Equip Cost**	**Total Cost**
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000	SF	600	8.33	0.52	1.185	$ 3,081	1 Carp	0.66	0.974	$ 3,213	0	0.680	$ -	$ 6,295
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"" thick, R30	5,000	SF	500	10.00	0.75	1.185	$ 4,444	1 Carp	0.79	0.974	$ 3,846	0	0.680	$ -	$ 8,291
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000	SF	475	10.53	1.08	1.185	$ 6,400	1 Carp	0.83	0.974	$ 4,041	0	0.680	$ -	$ 10,441
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"" thick, R30	5,000	SF	450	11.11	0.62	1.185	$ 3,674	1 Carp	0.88	0.974	$ 4,285	0	0.680	$ -	$ 7,959
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040	SF	1350	5.96	0.32	1.185	$ 3,049	1 Carp	0.29	0.974	$ 2,270	0	0.680	$ -	$ 5,320
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040	SF	1350	5.96	0.48	1.185	$ 4,574	1 Carp	0.29	0.974	$ 2,270	0	0.680	$ -	$ 6,844
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040	SF	1350	5.96	0.50	1.185	$ 4,764	1 Carp	0.29	0.974	$ 2,270	0	0.680	$ -	$ 7,035
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040	SF	1715	4.69	1.81	1.185	$ 17,247	G-2A	0.53	1.049	$ 4,470	0.39	0.680	$ 2,132	$ 23,849
																$ 40,099
														Overhead	10%	$ 4,010
														Profit and Contingency	5%	$ 2,205
														Total		$ 46,313.83

City Cost Table: Newport News, VA

Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	1.05	1.185	1.432	0.68	0.974	0.68
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	1.05	1.185	1.543	0.68	1.049	0.68

Labor Overhead and Labor Adjustment Factor Table

					(From Table in Back Cover of RSMeans)								Labor Overhead
Crew		**hour**	**daily**	**# Workers**	**B**	**C**	**D**	B + C + D	Workers x rate	Total Crew R	sum (BCD) x work rate	Total Labor OH	Total Labor OH / Total Crew Rate
G-2A	1 Roofer Composition	43.15	345.2	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.1	256.8	1	30.7	18.3	11	60	32.10		19.26		
	1 Buillding Laborer	39.15	313.2	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		**62.06**	0.543
1 Carp	1 Carpenter	49.25	394	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		**21.28**	0.432

Calculations for San Antonio, TX

	Division 07: Thermal and Moisture Protection		Key:	RS Means Data	Calculation	Adjustment Factor From City Cost Table										
ID	Activity	Quantity	Unit	Daily Output	Duration (days)	Material ($/Unit)	Material Adj.	Material Cost	Crew	Labor ($/Unit)	Labor Adj. Factor	Labor Cost	Equip ($/Unit)	Equip Adj. Factor	Equip Cost	Total Cost
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000	SF	600	8.33	0.52	1.095	$ 2,847	1 Carp	0.66	0.975	$ 3,218	0	0.681	$ -	$ 6,065
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"' thick, R30	5,000	SF	500	10.00	0.75	1.095	$ 4,106	1 Carp	0.79	0.975	$ 3,852	0	0.681	$ -	$ 7,958
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000	SF	475	10.53	1.08	1.095	$ 5,912	1 Carp	0.83	0.975	$ 4,047	0	0.681	$ -	$ 9,959
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"' thick, R30	5,000	SF	450	11.11	0.62	1.095	$ 3,394	1 Carp	0.88	0.975	$ 4,291	0	0.681	$ -	$ 7,685
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040	SF	1350	5.96	0.32	1.095	$ 2,817	1 Carp	0.29	0.975	$ 2,274	0	0.681	$ -	$ 5,091
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040	SF	1350	5.96	0.48	1.095	$ 4,225	1 Carp	0.29	0.975	$ 2,274	0	0.681	$ -	$ 6,499
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040	SF	1350	5.96	0.50	1.095	$ 4,401	1 Carp	0.29	0.975	$ 2,274	0	0.681	$ -	$ 6,675
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040	SF	1715	4.69	1.81	1.095	$ 15,933	G-2A	0.53	1.050	$ 4,476	0.39	0.681	$ 2,135	$ 22,545
																$ 38,188
														Overhead	10%	$ 3,819
														Profit and Contingency	5%	$ 2,100
														Total		$ 44,106.66

City Cost Table: San Antonio, TX

Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	0.97	1.095	1.432	0.681	0.975	0.681
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	0.97	1.095	1.543	0.681	1.050	0.681

Labor Overhead and Labor Adjustment Factor Table

					(From Table in Back Cover of RSMeans)								Labor Overhead
Crew		hour	daily	# Workers	B	C	D	B + C + D	Workers x rate	Total Crew Ra	sum (BCD) x work rate	Total Labor OH	Total Labor OH / Total Crew Rate
G-2A	1 Roofer Composition	43.15	345.2	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.1	256.8	1	30.7	18.3	11	60	32.10		19.26		
	1 Building Laborer	39.15	313.2	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		**62.06**	0.543
1 Carp	1 Carpenter	49.25	394	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		**21.28**	0.432

Calculations for Bakersfield, CA

Division 07: Thermal and Moisture Protection

Key:	RS Means Data	Calculation	Adjustment Factor From City Cost Table

ID	Activity	Quantity	Unit	Daily Output	Duration (days)	Material ($/Unit)	Material Adj.	Material Cost	Crew	Labor ($/Unit)	Labor Adj. Factor	Labor Cost	Equip ($/Unit)	Equip Adj. Factor	Equip Cost	Total Cost
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000	SF	600	8.33	0.52	1.139	$ 2,961	1 Carp	0.66	1.813	$ 5,983	0	1.266	$ -	$ 8,944
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"" thick, R30	5,000	SF	500	10.00	0.75	1.139	$ 4,271	1 Carp	0.79	1.813	$ 7,161	0	1.266	$ -	$ 11,432
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000	SF	475	10.53	1.08	1.139	$ 6,150	1 Carp	0.83	1.813	$ 7,524	0	1.266	$ -	$ 13,674
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"" thick, R30	5,000	SF	450	11.11	0.62	1.139	$ 3,531	1 Carp	0.88	1.813	$ 7,977	0	1.266	$ -	$ 11,507
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040	SF	1350	5.96	0.32	1.139	$ 2,930	1 Carp	0.29	1.813	$ 4,227	0	1.266	$ -	$ 7,157
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040	SF	1350	5.96	0.48	1.139	$ 4,395	1 Carp	0.29	1.813	$ 4,227	0	1.266	$ -	$ 8,622
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040	SF	1350	5.96	0.50	1.139	$ 4,578	1 Carp	0.29	1.813	$ 4,227	0	1.266	$ -	$ 8,805
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040	SF	1715	4.69	1.81	1.139	$ 16,574	G-2A	0.53	1.953	$ 8,321	0.39	1.266	$ 3,970	$ 28,865
																$ 51,804
														Overhead	10%	$ 5,180
														Profit and Contingency	5%	$ 2,849
														Total		$ 59,833.85

City Cost Table: Bakersfield, CA

Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	1.009	1.139	1.432	1.266	1.813	1.266
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	1.009	1.139	1.543	1.266	1.953	1.266

Labor Overhead and Labor Adjustment Factor Table

Crew		hour	daily	# Workers	B (From Table in Back Cover of RSMeans)	C	D	B + C + D	Workers x rate	Total Crew Ra	sum (BCD) x work rate	Total Labor OH	Labor Overhead: Total Labor OH / Total Crew Rate
G-2A	1 Roofer Composition	43.15	345.2	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.1	256.8	1	30.7	18.3	11	60	32.10		19.26		
	1 Building Laborer	39.15	313.2	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		**62.06**	0.543
1 Carp	1 Carpenter	49.25	394	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		**21.28**	0.432

Calculations for Rapid City, SD

Division 07: Thermal and Moisture Protection

Key: RS Means Data | Calculation | Adjustment Factor From City Cost Table

ID	Activity	Quantity	Unit	Daily Output	Duration (days)	Material ($/Unit)	Material Adj.	Material Cost	Crew	Labor ($/Unit)	Labor Adj. Factor	Labor Cost	Equip ($/Unit)	Equip Adj. Factor	Equip Cost	Total Cost
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000	SF	600	8.33	0.52	1.164	$ 3,026	1 Carp	0.66	0.759	$ 2,505	0	0.530	$ -	$ 5,530
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"" thick, R30	5,000	SF	500	10.00	0.75	1.164	$ 4,364	1 Carp	0.79	0.759	$ 2,998	0	0.530	$ -	$ 7,362
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000	SF	475	10.53	1.08	1.164	$ 6,284	1 Carp	0.83	0.759	$ 3,150	0	0.530	$ -	$ 9,434
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"" thick, R30	5,000	SF	450	11.11	0.62	1.164	$ 3,608	1 Carp	0.88	0.759	$ 3,339	0	0.530	$ -	$ 6,947
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040	SF	1350	5.96	0.32	1.164	$ 2,994	1 Carp	0.29	0.759	$ 1,770	0	0.530	$ -	$ 4,764
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040	SF	1350	5.96	0.48	1.164	$ 4,491	1 Carp	0.29	0.759	$ 1,770	0	0.530	$ -	$ 6,261
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040	SF	1350	5.96	0.50	1.164	$ 4,678	1 Carp	0.29	0.759	$ 1,770	0	0.530	$ -	$ 6,448
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040	SF	1715	4.69	1.81	1.164	$ 16,935	G-2A	0.53	0.818	$ 3,484	0.39	0.530	$ 1,662	$ 22,081
																$ 36,390
														Overhead	10%	$ 3,639
														Profit and Contingency	5%	$ 2,001
														Total		$ 42,030.10

City Cost Table: Rapid City, SD

Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	1.031	1.164	1.432	0.53	0.759	0.53
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	1.031	1.164	1.543	0.53	0.818	0.53

Labor Overhead and Labor Adjustment Factor Table

Crew		hour	daily	# Workers	B (From Table in Back Cover of RSMeans)	C	D	B + C + D	Workers x rate	Total Crew Ra	sum (BCD) x work rate	Total Labor OH	Labor Overhead Total Labor OH / Total Crew Rate
G-2A	1 Roofer Composition	43.15	345.2	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.1	256.8	1	30.7	18.3	11	60	32.10		19.26		
	1 Building Laborer	39.15	313.2	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		**62.06**	0.543
1 Carp	1 Carpenter	49.25	394	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		**21.28**	0.432

Calculations for Minot, ND

Division 07: Thermal and Moisture Protection

Key:	RS Means Data	Calculation	Adjustment Factor From City Cost Table

ID	Activity	Quantity	Unit	Daily Output	Duration (days)	Material ($/Unit)	Material Adj.	Material Cost	Crew	Labor ($/Unit)	Labor Adj. Factor	Labor Cost	Equip ($/Unit)	Equip Adj. Factor	Equip Cost	Total Cost
1	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 6" thick, R19	5,000	SF	600	8.33	0.52	1.225	$ 3,184	1 Carp	0.66	1.207	$ 3,984	0	0.843	$ -	$ 7,168
2	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 9 1/2"" thick, R30	5,000	SF	500	10.00	0.75	1.225	$ 4,593	1 Carp	0.79	1.207	$ 4,768	0	0.843	$ -	$ 9,361
3	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, paper or foil backing, 12" thick, R38	5,000	SF	475	10.53	1.08	1.225	$ 6,613	1 Carp	0.83	1.207	$ 5,010	0	0.843	$ -	$ 11,623
4	**Thermal Insulation** - Blanket Insulation Blanket insulation for floors/ceilings, fiberglass, blankets or batts, unfaced, 9 1/2"" thick, R30	5,000	SF	450	11.11	0.62	1.225	$ 3,797	1 Carp	0.88	1.207	$ 5,312	0	0.843	$ -	$ 9,108
5	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Kraft faced fiberglass 3 1/2" thick, R11, 15" wide	8,040	SF	1350	5.96	0.32	1.225	$ 3,151	1 Carp	0.29	1.207	$ 2,815	0	0.843	$ -	$ 5,966
6	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R13, 15" wide	8,040	SF	1350	5.96	0.48	1.225	$ 4,726	1 Carp	0.29	1.207	$ 2,815	0	0.843	$ -	$ 7,541
7	**Thermal Insulation** - Blanket Insulation Blanket insulation for walls, Foil faced fiberglass 3 1/2" thick, R15, 15" wide	8,040	SF	1350	5.96	0.50	1.225	$ 4,923	1 Carp	0.29	1.207	$ 2,815	0	0.843	$ -	$ 7,738
8	**Thermal Insulation** - Sprayed-On Insulation Closed cell, spray polyurethane foam, 2 pounds per cubic foot density	8,040	SF	1715	4.69	1.81	1.225	$ 17,822	G-2A	0.53	1.300	$ 5,541	0.39	0.843	$ 2,643	$ 26,007
																$ 44,476
														Overhead	10%	$ 4,448
														Profit and Contingency	5%	$ 2,446
														Total		$ 51,369.31

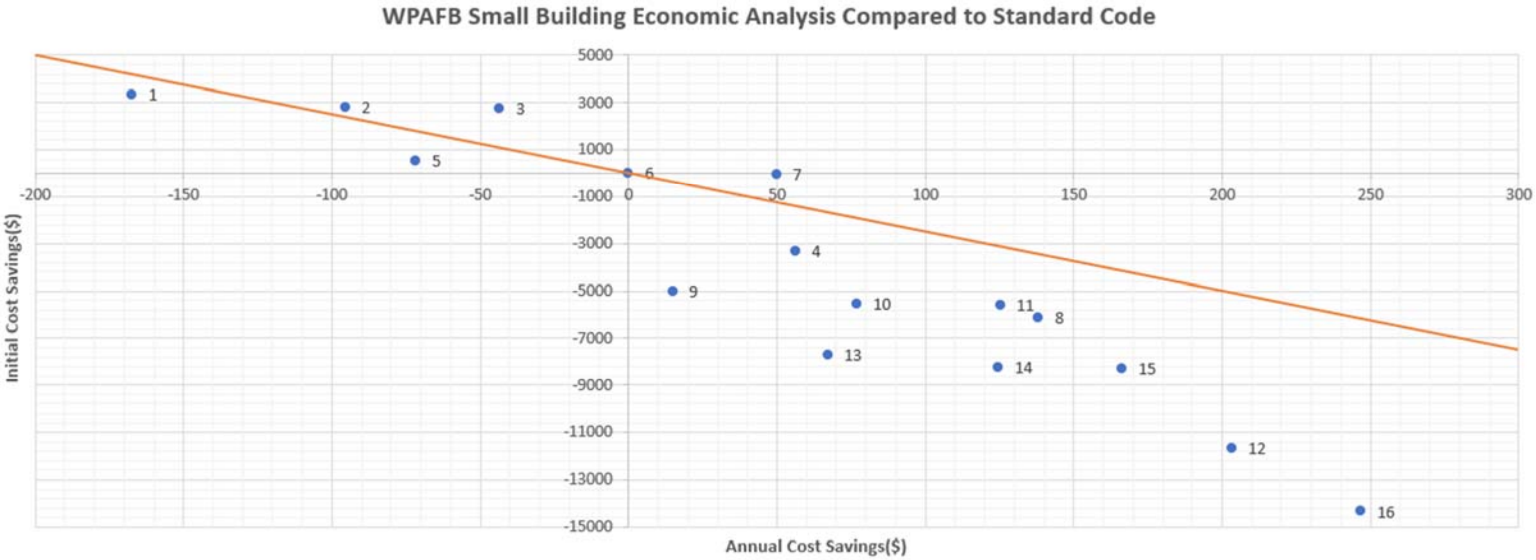
City Cost Table: Minot, ND

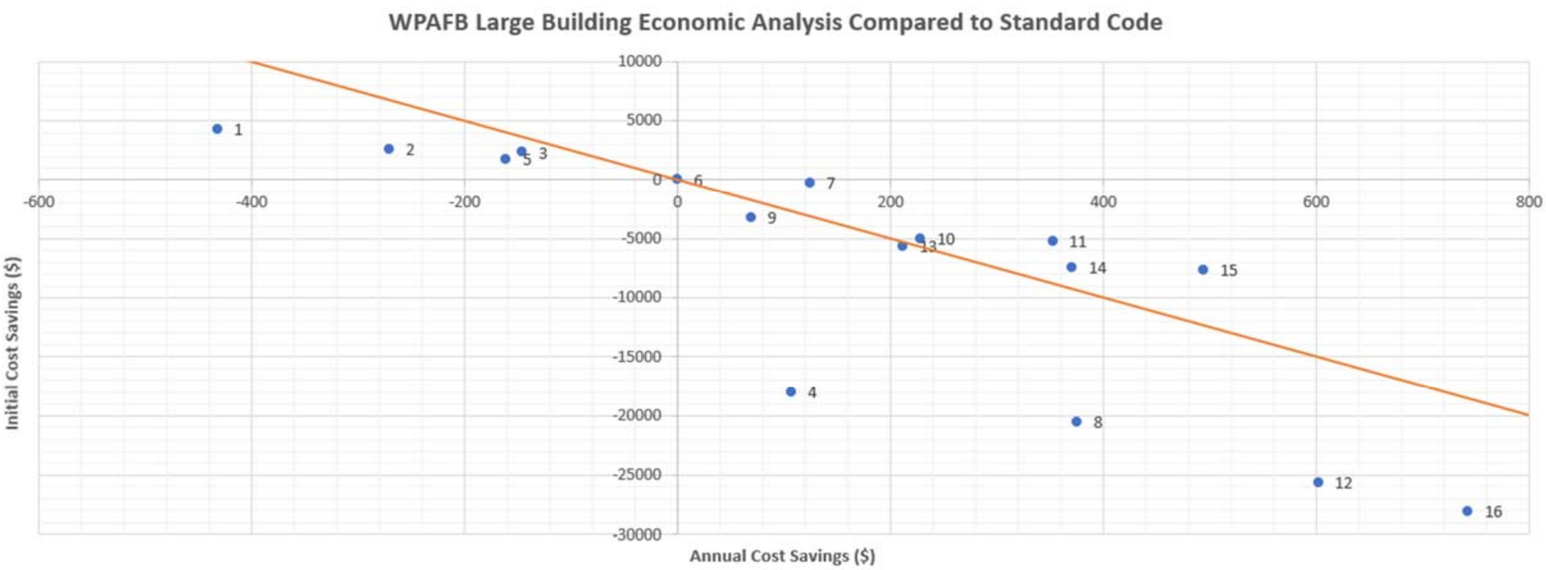
Division	Waste	Tax	Mat City Index	Material Adj. Factor	Labor Overhead	Inst. City Index	Labor Adj. Factor	Equip Adj. Factor
Division 07: Thermal and Moisture Protection - Caprpenter	1.05	1.075	1.085	1.225	1.432	0.843	1.207	0.843
Division 07: Thermal and Moisture Protection - Crew G-2A	1.05	1.075	1.085	1.225	1.543	0.843	1.300	0.843

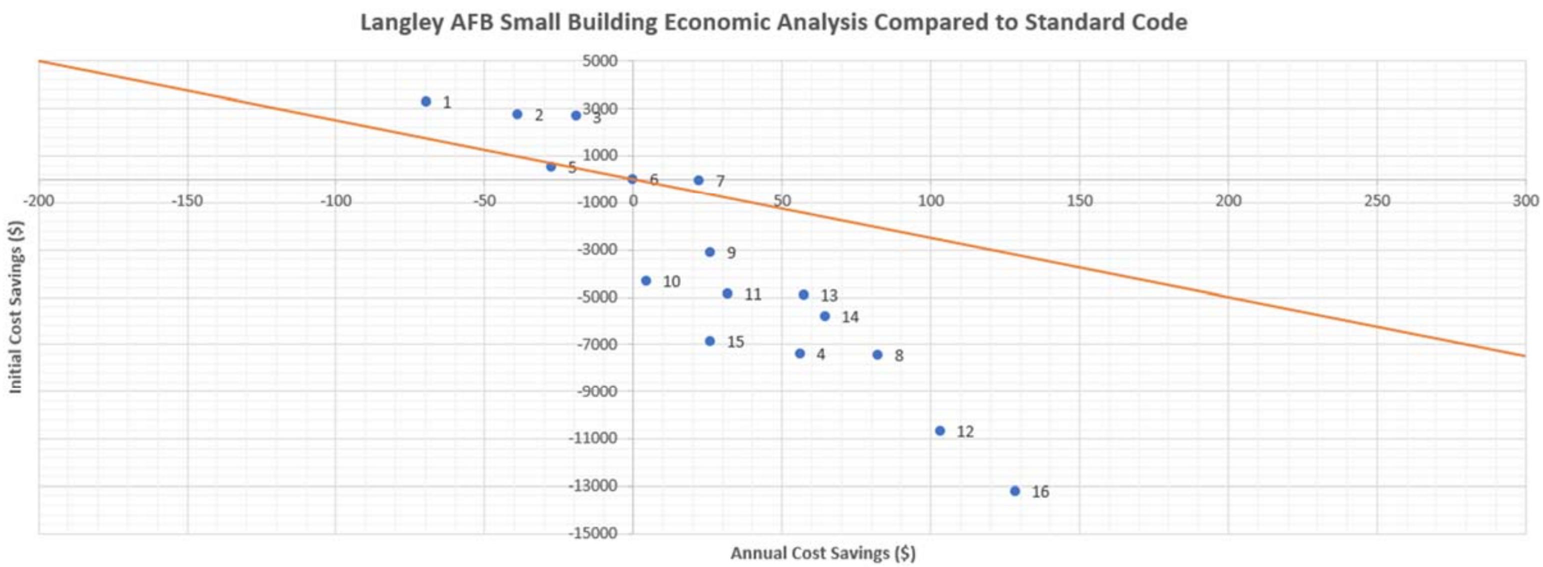
Labor Overhead and Labor Adjustment Factor Table

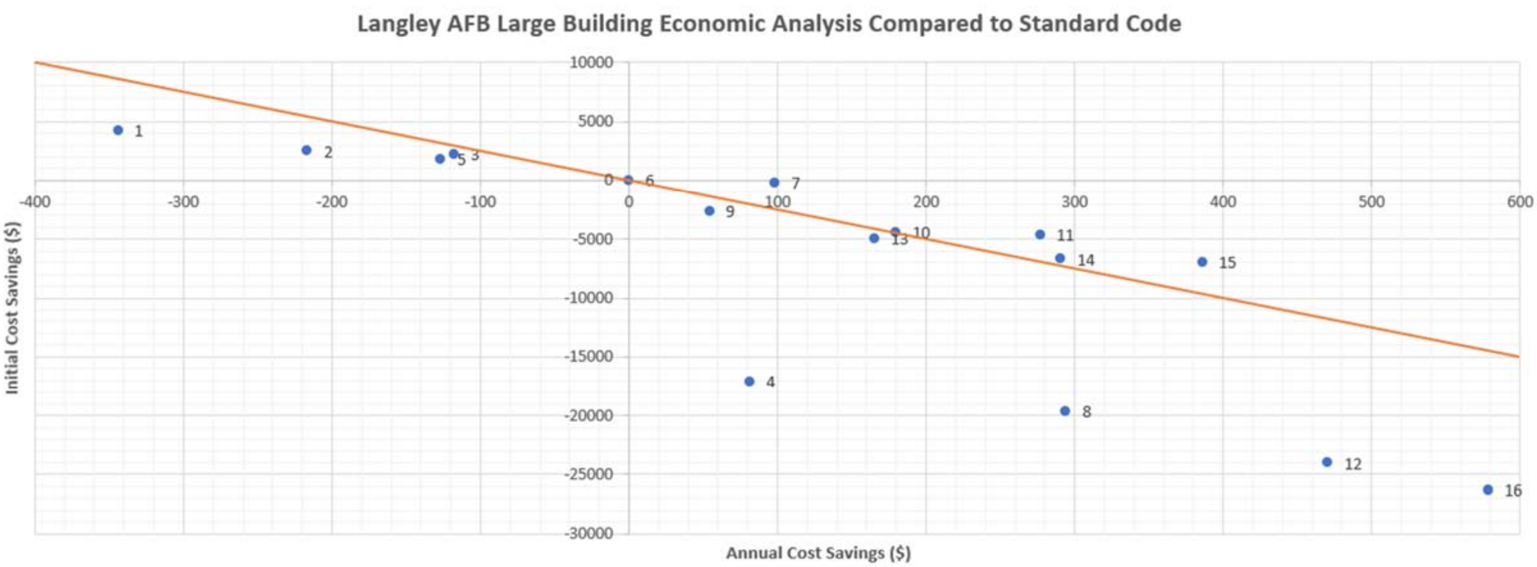
Crew		hour	daily	# Workers	B (From Table in Back Cover of RSMeans)	C	D	B + C + D	Workers x rate	Total Crew Rate	sum (BCD) x work rate	Total Labor OH	Labor Overhead: Total Labor OH / Total Crew Rate
G-2A	1 Roofer Composition	43.15	345.2	1	30.7	18.3	11	60.0	43.15		25.89		
	1 Roofer Helper	32.1	256.8	1	30.7	18.3	11	60	32.10		19.26		
	1 Building Laborer	39.15	313.2	1	13.9	18.3	11	43.2	39.15		16.91		
										114.40		**62.06**	0.543
1 Carp	1 Carpenter	49.25	394	1	13.9	18.3	11	43.2	49.25		21.28		
										49.25		**21.28**	0.432

Appendix E: Scatter Plots to Identify the Areas of Interest for High Performing Insulation Configurations

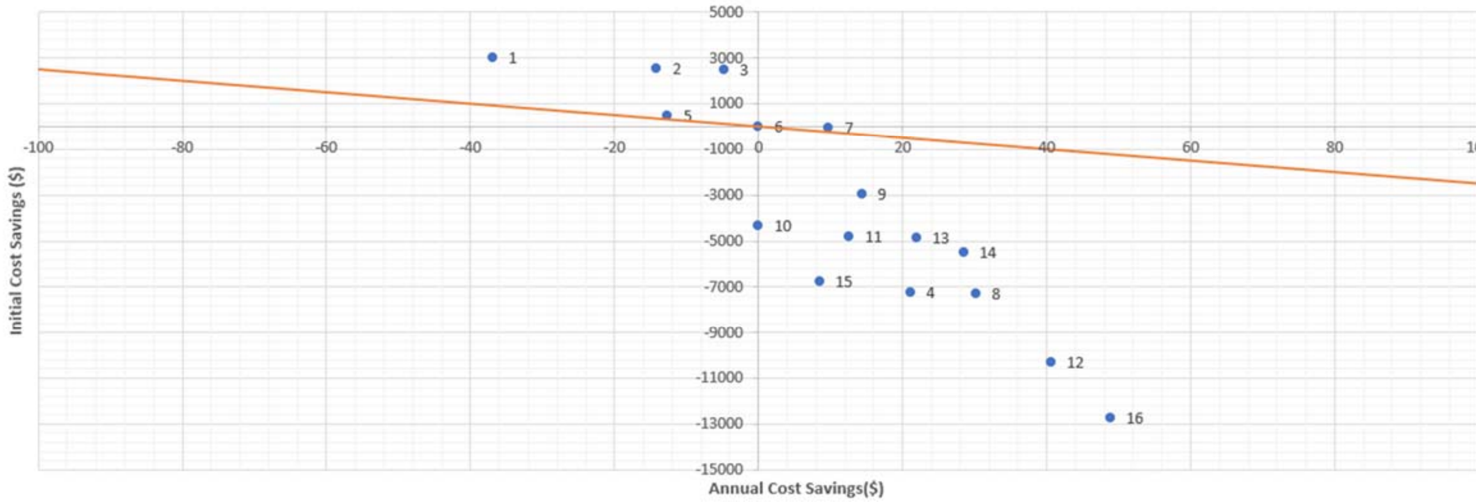




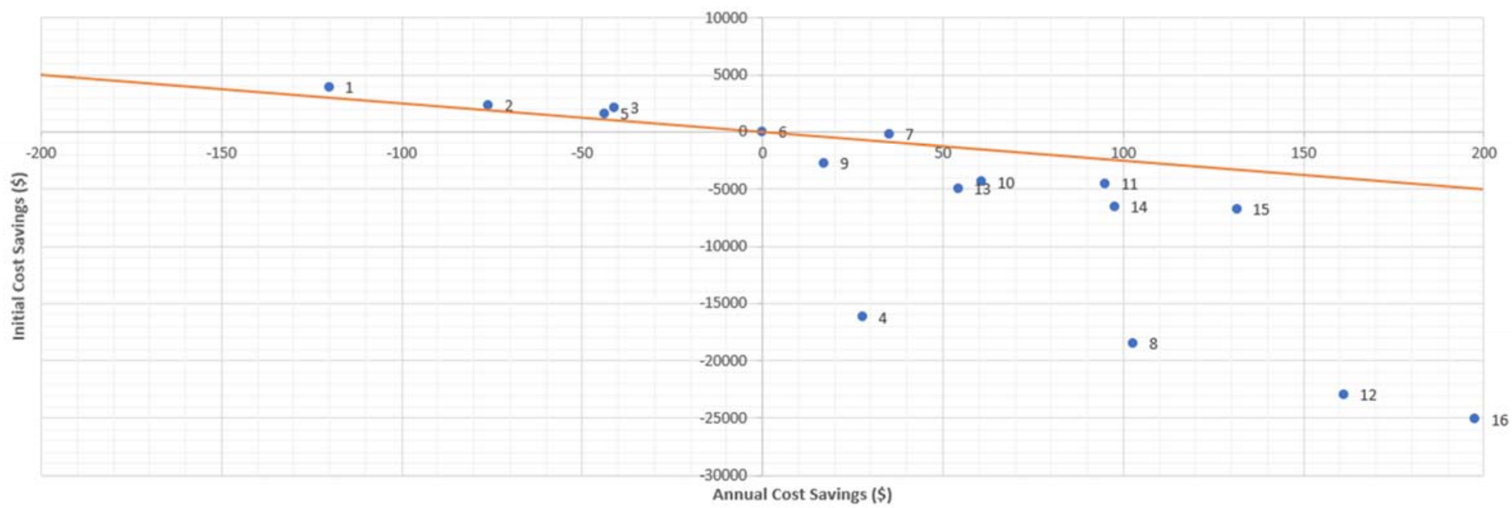

Langley AFB Small Building Economic Analysis Compared to Standard Code
Initial Cost Savings ($)
Annual Cost Savings ($)
5000
3000
1000
-1000
-3000
-5000
-7000
-9000
-11000
-13000
-15000
-200
-150
-100
-50
0
50
100
150
200
250
300
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

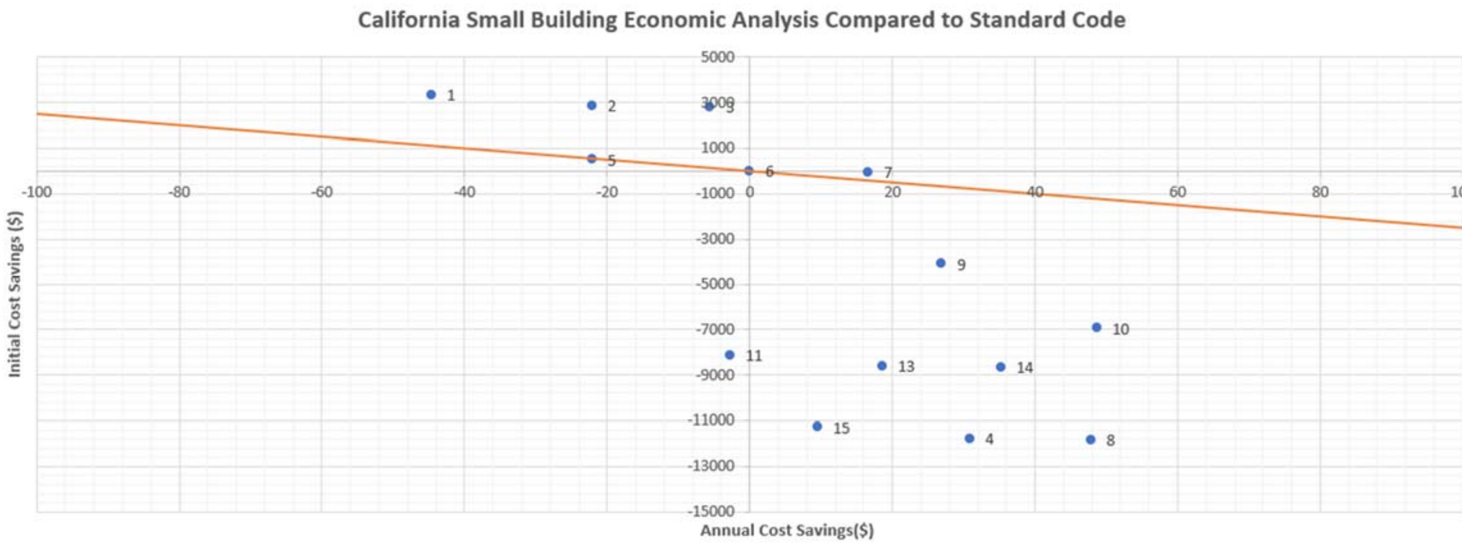

Langley AFB Large Building Economic Analysis Compared to Standard Code
Initial Cost Savings ($)
Annual Cost Savings ($)
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-400
-300
-200
-100
0
100
200
300
400
500
600
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

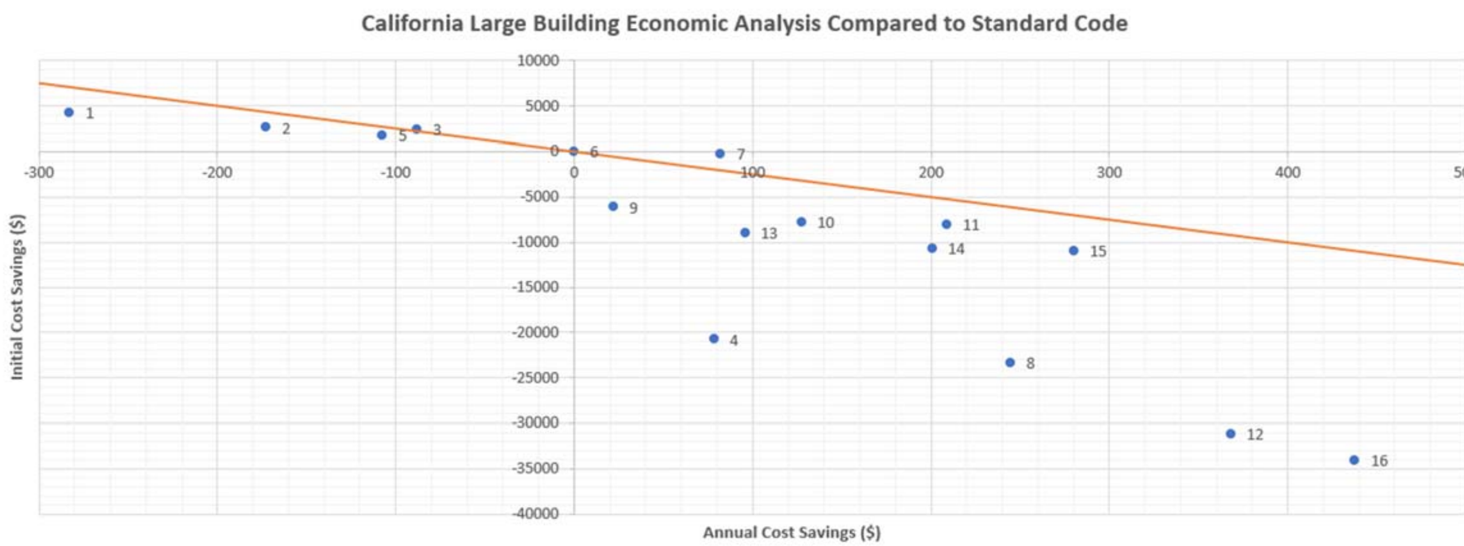
JB San Antonio Small Building Economic Analysis Compared to Standard Code

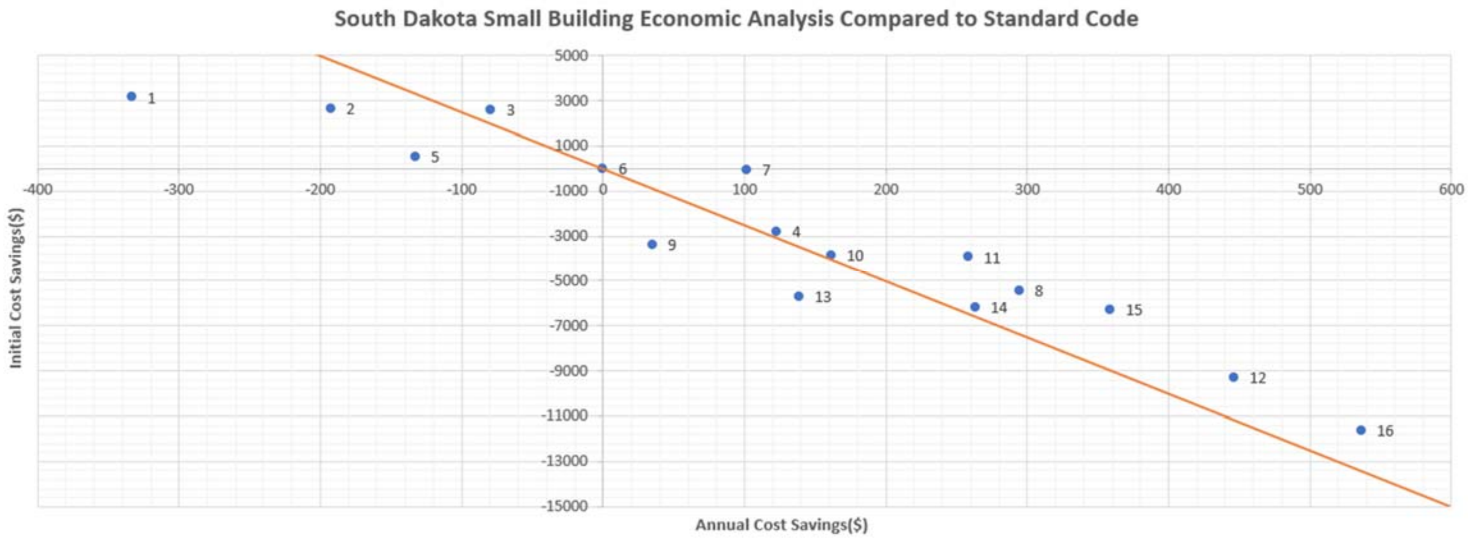


JB San Antonio Large Building Economic Analysis Compared to Standard Code




California Small Building Economic Analysis Compared to Standard Code
Initial Cost Savings ($)
Annual Cost Savings($)


California Large Building Economic Analysis Compared to Standard Code
Initial Cost Savings ($)
Annual Cost Savings ($)


South Dakota Small Building Economic Analysis Compared to Standard Code
Initial Cost Savings($)
Annual Cost Savings($)
5000
3000
1000
-1000
-3000
-5000
-7000
-9000
-11000
-13000
-15000
-400
-300
-200
-100
0
100
200
300
400
500
600
1
2
3
4
5
6
7
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10
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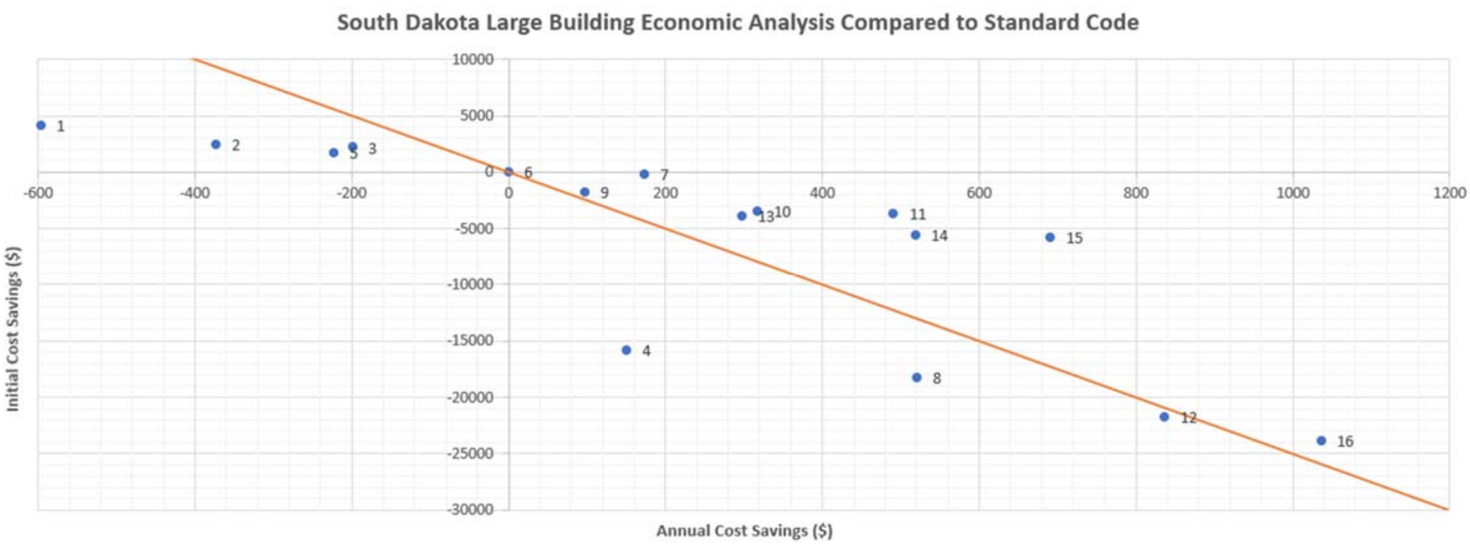
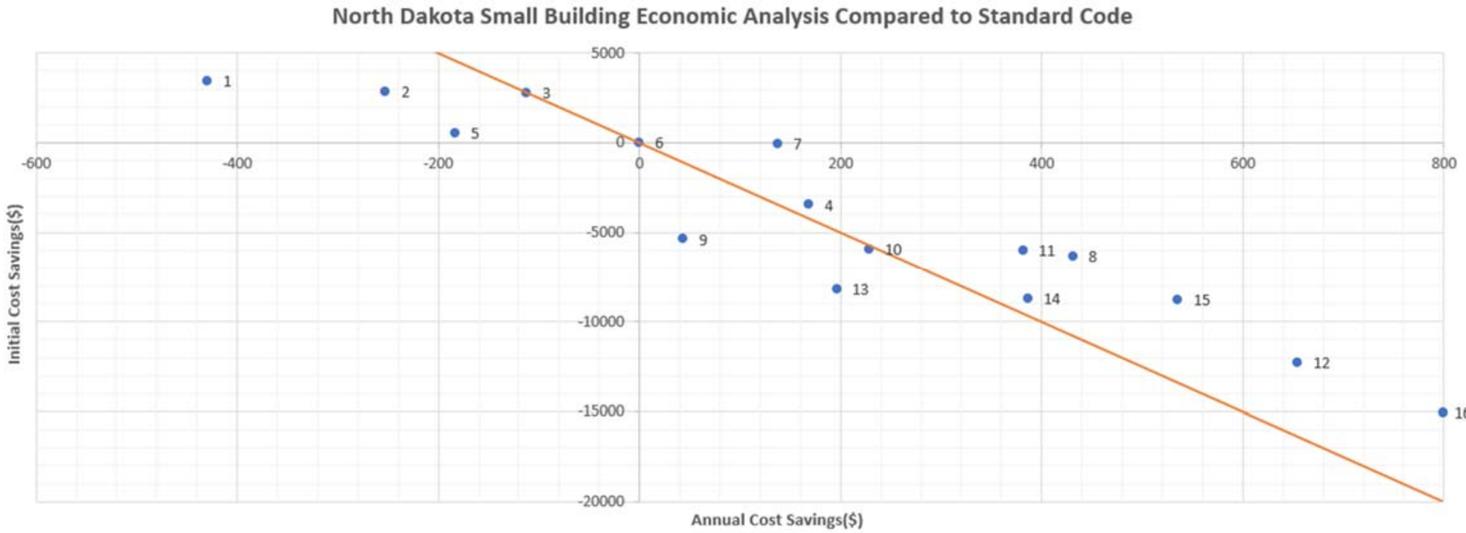
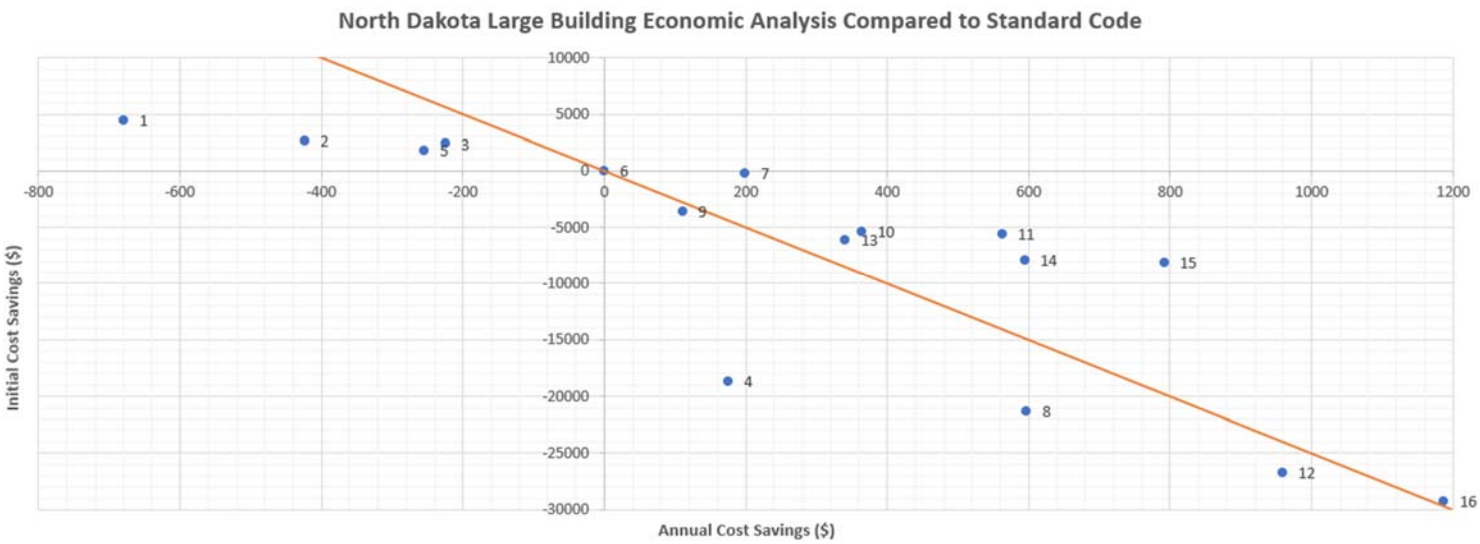
14
15
16


South Dakota Large Building Economic Analysis Compared to Standard Code
Initial Cost Savings ($)
Annual Cost Savings ($)
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-600
-400
-200
0
200
400
600
800
1000
1200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16


North Dakota Small Building Economic Analysis Compared to Standard Code
Initial Cost Savings($)
Annual Cost Savings($)
5000
0
-5000
-10000
-15000
-20000
-600
-400
-200
200
400
600
800
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16


North Dakota Large Building Economic Analysis Compared to Standard Code
Initial Cost Savings ($)
Annual Cost Savings ($)
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-800
-600
-400
-200
200
400
600
800
1000
1200
1
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16

Appendix F: Internal Rate of Return Calculations

The following tables provide the internal rate of return calculations made using Microsoft Excel for the analyses found in chapter 4. Each analysis was performed for each insulation configuration.

(1) Wright Patterson AFB, OH – Small Building

Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)
0	0	$ 10,186.81			
1	$ 13,337.92	$ 7,613.89	-13337.92	2572.93	19.04%
2	$ 13,866.97	$ 7,542.12	-13866.97	2644.69	18.82%
3	$ 13,933.10	$ 7,489.95	-13933.10	2696.86	19.11%
5	$ 16,140.02	$ 7,518.31	-16140.02	2668.50	16.14%
6	$ 16,669.07	$ 7,446.55	-16669.07	2740.27	16.04%
7	$ 16,735.20	$ 7,396.73	-16735.20	2790.09	16.29%
4	$ 19,984.52	$ 7,390.32	-19984.52	2796.50	13.39%
9	$ 21,685.46	$ 7,431.72	-21685.46	2755.09	11.95%
10	$ 22,214.51	$ 7,369.65	-22214.51	2817.17	11.92%
11	$ 22,280.64	$ 7,321.32	-22280.64	2865.49	12.13%
8	$ 22,786.62	$ 7,308.35	-22786.62	2878.46	11.87%
13	$ 24,370.28	$ 7,379.41	-24370.28	2807.41	10.59%
14	$ 24,899.32	$ 7,321.89	-24899.32	2864.92	10.57%
15	$ 24,965.45	$ 7,280.27	-24965.45	2906.54	10.73%
12	$ 28,332.07	$ 7,243.29	-28332.07	2943.53	9.25%
16	$ 31,016.88	$ 7,199.81	-31016.88	2987.00	8.33%

Compared to Standard				WPAFB - Small Building				Treasury Notes and Bonds	
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**	**MARR should be ____ iRR to merit selection over comparison**	**MARR 0%**	**MARR 0.4%**	**MARR 6%**
1	$ 13,337.92	$ 7,613.89	3331.15	-167.34	1.84%	above	No	No	Yes
2	$ 13,866.97	$ 7,542.12	2802.10	-95.57	-1.19%	above	Yes	Yes	Yes
3	$ 13,933.10	$ 7,489.95	2735.97	-43.40	-6.13%	above	Yes	Yes	Yes
5	$ 16,140.02	$ 7,518.31	529.05	-71.77	12.91%	above	No	No	No
6	$ 16,669.07	$ 7,446.55	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	
7	$ 16,735.20	$ 7,396.73	-66.13	49.82	75.33%	below	Yes	Yes	Yes
4	$ 19,984.52	$ 7,390.32	-3315.45	56.23	-5.74%	below	No	No	No
9	$ 21,685.46	$ 7,431.72	-5016.40	14.82	-14.49%	below	No	No	No
10	$ 22,214.51	$ 7,369.65	-5545.44	76.90	-6.90%	below	No	No	No
11	$ 22,280.64	$ 7,321.32	-5611.58	125.22	-4.06%	below	No	No	No
8	$ 22,786.62	$ 7,308.35	-6117.55	138.19	-3.99%	below	No	No	No
13	$ 24,370.28	$ 7,379.41	-7701.21	67.14	-9.39%	below	No	No	No
14	$ 24,899.32	$ 7,321.89	-8230.26	124.65	-6.40%	below	No	No	No
15	$ 24,965.45	$ 7,280.27	-8296.39	166.27	-4.74%	below	No	No	No
12	$ 28,332.07	$ 7,243.29	-11663.00	203.26	-5.58%	below	No	No	No
16	$ 31,016.88	$ 7,199.81	-14347.81	246.73	-5.66%	below	No	No	No

Incremental Analysis			WPAFB - Small Building				MARR = 0.4%
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Compared to Configuration ____**	**Rate of Return (iRR)**	**Better than Previous**
0	0	$10,186.81					
1	$ 13,337.92	$ 7,613.89	-13337.92	2572.93	0	19.04%	Yes
2	$ 13,866.97	$ 7,542.12	-529.05	71.77	1	12.91%	Yes
3	**$ 13,933.10**	**$ 7,489.95**	**-66.13**	**52.17**	**2**	**78.89%**	**Yes**
5	$ 16,140.02	$ 7,518.31	-2206.92	-28.36	3	N/A	No
6	$ 16,669.07	$ 7,446.55	-2735.97	43.40	3	-6.13%	No
7	$ 16,735.20	$ 7,396.73	-2802.10	93.22	3	-1.37%	No
4	$ 19,984.52	$ 7,390.32	-6051.42	99.64	3	-5.92%	No
9	$ 21,685.46	$ 7,431.72	-7752.36	58.23	3	-10.15%	No
10	$ 22,214.51	$ 7,369.65	-8281.41	120.30	3	-6.64%	No
11	$ 22,280.64	$ 7,321.32	-8347.54	168.63	3	-4.69%	No
8	$ 22,786.62	$ 7,308.35	-8853.52	181.60	3	-4.59%	No
13	$ 24,370.28	$ 7,379.41	-10437.18	110.54	3	-8.38%	No
14	$ 24,899.32	$ 7,321.89	-10966.22	168.06	3	-6.33%	No
15	$ 24,965.45	$ 7,280.27	-11032.36	209.68	3	-5.06%	No
12	$ 28,332.07	$ 7,243.29	-14398.97	246.66	3	-5.68%	No
16	$ 31,016.88	$ 7,199.81	-17083.78	290.14	3	-5.73%	No

		WPAFB Small Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	***** **3**	7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(2) Wright Patterson AFB, OH – Large Building

Compared to Baseline (No Insulation)			WPAFB - Large Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 40,007.73			
1	$ 16,930.69	$ 31,276.19	-16930.69	8731.54	51.57%
2	$ 18,711.76	$ 31,114.88	-18711.76	8892.86	47.52%
3	$ 18,934.39	$ 30,989.76	-18934.39	9017.97	47.62%
5	$ 19,475.51	$ 31,004.87	-19475.51	9002.86	46.22%
6	$ 21,256.58	$ 30,844.13	-21256.58	9163.61	43.10%
7	$ 21,479.21	$ 30,719.58	-21479.21	9288.15	43.24%
9	$ 24,511.79	$ 30,774.87	-24511.79	9232.86	37.65%
10	$ 26,292.85	$ 30,615.56	-26292.85	9392.18	35.70%
11	$ 26,515.49	$ 30,491.58	-26515.49	9516.15	35.87%
13	$ 26,950.09	$ 30,632.09	-26950.09	9375.65	34.77%
14	$ 28,731.15	$ 30,473.06	-28731.15	9534.67	33.16%
15	$ 28,953.79	$ 30,349.65	-28953.79	9658.08	33.33%
4	$ 39,306.82	$ 30,736.97	-39306.82	9270.77	23.46%
8	$ 41,851.64	$ 30,468.50	-41851.64	9539.24	22.65%
12	$ 46,887.92	$ 30,241.92	-46887.92	9765.81	20.64%
16	$ 49,326.22	$ 30,101.13	-49326.22	9906.60	19.87%

Compared to Standard				WPAFB - Large Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be ____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 16,930.69	$ 31,276.19	4325.88	-432.06	8.77%	above	No	No	No
2	$ 18,711.76	$ 31,114.88	2544.82	-270.75	9.55%	above	No	No	No
3	$ 18,934.39	$ 30,989.76	2322.18	-145.63	3.81%	above	No	No	Yes
5	$ 19,475.51	$ 31,004.87	1781.07	-160.74	7.57%	above	No	No	No
6	$ 21,256.58	$ 30,844.13	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 21,479.21	$ 30,719.58	-222.63	124.54	55.94%	below	Yes	Yes	Yes
9	$ 24,511.79	$ 30,774.87	-3255.21	69.25	-4.36%	below	No	No	No
10	$ 26,292.85	$ 30,615.56	-5036.28	228.57	1.00%	below	Yes	Yes	No
11	$ 26,515.49	$ 30,491.58	-5258.91	352.54	4.44%	below	Yes	Yes	No
13	$ 26,950.09	$ 30,632.09	-5693.51	212.04	-0.54%	below	No	No	No
14	$ 28,731.15	$ 30,473.06	-7474.58	371.07	1.74%	below	Yes	Yes	No
15	$ 28,953.79	$ 30,349.65	-7697.21	494.47	4.03%	below	Yes	Yes	No
4	$ 39,306.82	$ 30,736.97	-18050.25	107.16	-11.30%	below	No	No	No
8	$ 41,851.64	$ 30,468.50	-20595.06	375.63	-5.31%	below	No	No	No
12	$ 46,887.92	$ 30,241.92	-25631.34	602.21	-3.73%	below	No	No	No
16	$ 49,326.22	$ 30,101.13	-28069.64	742.99	-2.95%	below	No	No	No

Incremental Analysis			WPAFB - Large Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	0	$40,007.73					
1	$ 16,930.69	$31,276.19	-16930.69	8731.54	0	51.57%	Yes
2	$ 18,711.76	$31,114.88	-1781.07	161.31	1	7.61%	Yes
3	$ 18,934.39	$30,989.76	-222.63	125.12	2	56.20%	Yes
5	$ 19,475.51	$31,004.87	-541.12	-15.11	3	N/A	No
6	$ 21,256.58	$30,844.13	-2322.18	145.63	3	3.81%	Yes
7	$ 21,479.21	$30,719.58	-222.63	124.54	6	55.94%	Yes
9	$ 24,511.79	$30,774.87	-3032.58	-55.29	7	N/A	No
10	$ 26,292.85	$30,615.56	-4813.64	104.03	7	-4.27%	No
11	$ 26,515.49	$30,491.58	-5036.28	228.00	7	0.98%	Yes
13	$ 26,950.09	$30,632.09	-434.60	-140.50	11	N/A	No
14	$ 28,731.15	$30,473.06	-2215.67	18.52	11	-9.61%	No
15	**$ 28,953.79**	**$30,349.65**	**-2438.30**	**141.93**	**11**	**3.12%**	**Yes**
4	$ 39,306.82	$30,736.97	-10353.04	-387.31	15	N/A	No
8	$ 41,851.64	$30,468.50	-12897.85	-118.84	15	N/A	No
12	$ 46,887.92	$30,241.92	-17934.13	107.73	15	-11.24%	No
16	$ 49,326.22	$30,101.13	-20372.43	248.52	15	-7.61%	No

		WPAFB Large Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	7	11	***** **15**
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(3) Langley AFB, VA – Small Building

Compared to Baseline (No Insulation)			Langley - Small Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	$ -	$ 9,571.83			
1	$12,369.08	$ 7,887.26	-12369.08	1684.57	12.97%
2	$12,892.15	$ 7,856.41	-12892.15	1715.42	12.62%
3	$12,957.53	$ 7,836.81	-12957.53	1735.01	12.72%
5	$15,103.78	$ 7,845.15	-15103.78	1726.67	10.49%
6	$15,626.85	$ 7,817.68	-15626.85	1754.14	10.25%
7	$15,692.23	$ 7,795.36	-15692.23	1776.47	10.36%
4	$18,726.18	$ 7,791.63	-18726.18	1780.20	8.17%
9	$19,952.28	$ 7,813.31	-19952.28	1758.51	7.30%
10	$20,475.35	$ 7,785.84	-20475.35	1785.98	7.18%
11	$20,540.74	$ 7,760.25	-20540.74	1811.57	7.31%
8	$21,460.88	$ 7,753.23	-21460.88	1818.60	6.86%
13	$22,490.62	$ 7,791.76	-22490.62	1780.06	6.12%
14	$23,013.69	$ 7,761.57	-23013.69	1810.26	6.06%
15	$23,079.08	$ 7,735.32	-23079.08	1836.51	6.18%
12	$26,309.39	$ 7,714.53	-26309.39	1857.30	4.95%
16	$28,847.73	$ 7,689.26	-28847.73	1882.56	4.18%

Compared to Standard				Langley - Small Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 12,369.08	$ 7,887.26	3257.77	-69.58	-4.34%	above	Yes	Yes	Yes
2	$ 12,892.15	$ 7,856.41	2734.70	-38.73	-6.78%	above	Yes	Yes	Yes
3	$ 12,957.53	$ 7,836.81	2669.32	-19.13	-10.38%	above	Yes	Yes	Yes
5	$ 15,103.78	$ 7,845.15	523.07	-27.47	2.21%	above	No	No	Yes
6	$ 15,626.85	$ 7,817.68	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 15,692.23	$ 7,795.36	-65.38	22.32	34.12%	below	Yes	Yes	Yes
4	$ 18,726.18	$ 7,791.63	-3099.33	26.06	-9.58%	below	No	No	No
9	$ 19,952.28	$ 7,813.31	-4325.43	4.37	-18.90%	below	No	No	No
10	$ 20,475.35	$ 7,785.84	-4848.50	31.84	-10.81%	below	No	No	No
11	$ 20,540.74	$ 7,760.25	-4913.89	57.43	-7.85%	below	No	No	No
8	$ 21,460.88	$ 7,753.23	-5834.03	64.45	-8.15%	below	No	No	No
13	$ 22,490.62	$ 7,791.76	-6863.77	25.92	-13.40%	below	No	No	No
14	$ 23,013.69	$ 7,761.57	-7386.84	56.11	-10.09%	below	No	No	No
15	$ 23,079.08	$ 7,735.32	-7452.23	82.36	-8.15%	below	No	No	No
12	$ 26,309.39	$ 7,714.53	-10682.54	103.16	-8.86%	below	No	No	No
16	$ 28,847.73	$ 7,689.26	-13220.88	128.42	-8.83%	below	No	No	No

Incremental Analysis			Langley - Small Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	$ -	$ 9,571.83					
1	$ 12,369.08	$ 7,887.26	-12369.08	1684.57	0	12.97%	Yes
2	$ 12,892.15	$ 7,856.41	-523.07	30.85	1	3.24%	Yes
3	**$ 12,957.53**	**$ 7,836.81**	**-65.38**	**19.60**	2	**29.93%**	**Yes**
5	$ 15,103.78	$ 7,845.15	-2146.25	-8.34	3	N/A	No
6	$ 15,626.85	$ 7,817.68	-2669.32	19.13	3	-10.38%	No
7	$ 15,692.23	$ 7,795.36	-2734.70	41.45	3	-6.40%	No
4	$ 18,726.18	$ 7,791.63	-5768.65	45.19	3	-9.94%	No
9	$ 19,952.28	$ 7,813.31	-6994.75	23.50	3	-13.92%	No
10	$ 20,475.35	$ 7,785.84	-7517.82	50.97	3	-10.65%	No
11	$ 20,540.74	$ 7,760.25	-7583.21	76.56	3	-8.63%	No
8	$ 21,460.88	$ 7,753.23	-8503.35	83.58	3	-8.77%	No
13	$ 22,490.62	$ 7,791.76	-9533.09	45.05	3	-12.38%	No
14	$ 23,013.69	$ 7,761.57	-10056.16	75.24	3	-10.17%	No
15	$ 23,079.08	$ 7,735.32	-10121.54	101.49	3	-8.67%	No
12	$ 26,309.39	$ 7,714.53	-13351.86	122.29	3	-9.14%	No
16	$ 28,847.73	$ 7,689.26	-15890.19	147.55	3	-9.07%	No

		Langley Small Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	***** **3**	7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(4) Langley AFB, VA – Large Building

Compared to Baseline (No Insulation)			Langley - Large Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 39,877.78			
1	$ 15,720.10	$ 33,235.54	-15720.10	6642.24	42.25%
2	$ 17,481.04	$ 33,107.93	-17481.04	6769.85	38.72%
3	$ 17,701.16	$ 33,008.93	-17701.16	6868.84	38.79%
5	$ 18,203.71	$ 33,018.14	-18203.71	6859.64	37.67%
6	$ 19,964.65	$ 32,891.52	-19964.65	6986.26	34.97%
7	$ 20,184.77	$ 32,793.18	-20184.77	7084.60	35.08%
9	$ 22,607.03	$ 32,837.25	-22607.03	7040.52	31.11%
10	$ 24,367.98	$ 32,711.62	-24367.98	7166.16	29.36%
11	$ 24,588.09	$ 32,614.60	-24588.09	7263.18	29.49%
13	$ 24,912.31	$ 32,726.09	-24912.31	7151.69	28.65%
14	$ 26,673.25	$ 32,600.78	-26673.25	7277.00	27.22%
15	$ 26,893.37	$ 32,505.40	-26893.37	7372.37	27.35%
4	$ 37,121.62	$ 32,809.96	-37121.62	7067.82	18.78%
8	$ 39,605.23	$ 32,597.16	-39605.23	7280.61	18.10%
12	$ 44,008.55	$ 32,420.88	-44008.55	7456.90	16.58%
16	$ 46,313.83	$ 32,313.00	-46313.83	7564.77	15.93%

Compared to Standard				Langley - Large Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 15,720.10	$ 33,235.54	4244.55	-344.02	6.38%	above	No	No	No
2	$ 17,481.04	$ 33,107.93	2483.61	-216.41	7.17%	above	No	No	No
3	$ 17,701.16	$ 33,008.93	2263.49	-117.41	2.11%	above	No	No	Yes
5	$ 18,203.71	$ 33,018.14	1760.94	-126.62	5.13%	above	No	No	Yes
6	$ 19,964.65	$ 32,891.52	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 20,184.77	$ 32,793.18	-220.12	98.34	44.67%	below	Yes	Yes	Yes
9	$ 22,607.03	$ 32,837.25	-2642.38	54.27	-4.58%	below	No	No	No
10	$ 24,367.98	$ 32,711.62	-4403.33	179.90	0.16%	below	Yes	No	No
11	$ 24,588.09	$ 32,614.60	-4623.44	276.92	3.38%	below	Yes	Yes	No
13	$ 24,912.31	$ 32,726.09	-4947.66	165.43	-1.33%	below	No	No	No
14	$ 26,673.25	$ 32,600.78	-6708.60	290.74	0.63%	below	Yes	Yes	No
15	$ 26,893.37	$ 32,505.40	-6928.72	386.12	2.73%	below	Yes	Yes	No
4	$ 37,121.62	$ 32,809.96	-17156.97	81.56	-12.35%	below	No	No	No
8	$ 39,605.23	$ 32,597.16	-19640.58	294.36	-6.46%	below	No	No	No
12	$ 44,008.55	$ 32,420.88	-24043.90	470.64	-4.88%	below	No	No	No
16	$ 46,313.83	$ 32,313.00	-26349.18	578.52	-4.17%	below	No	No	No

Incremental Analysis			Langley - Large Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	0	$39,877.78					
1	$ 15,720.10	$33,235.54	-15720.10	6642.24	0	42.25%	Yes
2	$ 17,481.04	$33,107.93	-1760.94	127.61	1	5.21%	Yes
3	$ 17,701.16	$33,008.93	-220.12	99.00	2	44.97%	Yes
5	$ 18,203.71	$33,018.14	-502.55	-9.21	3	N/A	No
6	$ 19,964.65	$32,891.52	-2263.49	117.41	3	2.11%	Yes
7	$ 20,184.77	$32,793.18	-220.12	98.34	6	44.67%	Yes
9	$ 22,607.03	$32,837.25	-2422.27	-44.07	7	N/A	No
10	$ 24,367.98	$32,711.62	-4183.21	81.56	7	-4.90%	No
11	$ 24,588.09	$32,614.60	-4403.33	178.59	7	0.11%	No
13	$ 24,912.31	$32,726.09	-4727.54	67.09	7	-6.77%	No
14	$ 26,673.25	$32,600.78	-6488.48	192.40	7	-2.18%	No
15	**$ 26,893.37**	**$32,505.40**	**-6708.60**	**287.78**	**7**	**0.55%**	**Yes**
4	$ 37,121.62	$32,809.96	-10228.25	-304.55	15	N/A	No
8	$ 39,605.23	$32,597.16	-12711.86	-91.76	15	N/A	No
12	$ 44,008.55	$32,420.88	-17115.18	84.52	15	-12.17%	No
16	$ 46,313.83	$32,313.00	-19420.46	192.40	15	-8.73%	No

		Langley Large Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	7	11	***** **15**
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(5) JB San Antonio, TX – Small Building

Compared to Baseline (No Insulation)			San Antonio - Small Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 6,626.53			
1	$11,867.06	$ 5,344.45	-11867.06	1282.08	9.75%
2	$12,350.28	$ 5,321.66	-12350.28	1304.88	9.46%
3	$12,410.68	$ 5,312.33	-12410.68	1314.20	9.49%
5	$14,412.64	$ 5,320.14	-14412.64	1306.39	7.62%
6	$14,895.85	$ 5,307.54	-14895.85	1318.99	7.35%
7	$14,956.26	$ 5,297.76	-14956.26	1328.77	7.39%
4	$17,855.22	$ 5,293.20	-17855.22	1333.33	5.52%
9	$19,233.15	$ 5,307.54	-19233.15	1318.99	4.66%
10	$19,716.37	$ 5,294.94	-19716.37	1331.60	4.51%
11	$19,776.77	$ 5,285.61	-19776.77	1340.92	4.55%
8	$20,400.80	$ 5,279.08	-20400.80	1347.45	4.30%
13	$21,640.61	$ 5,299.06	-21640.61	1327.47	3.60%
14	$22,123.83	$ 5,286.46	-22123.83	1340.07	3.48%
15	$22,184.23	$ 5,277.35	-22184.23	1349.18	3.52%
12	$25,221.31	$ 5,266.93	-25221.31	1359.60	2.44%
16	$27,628.77	$ 5,258.67	-27628.77	1367.86	1.71%

Compared to Standard				San Antonio - Small Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 11,867.06	$ 5,344.45	3028.80	-36.92	-7.62%	above	Yes	Yes	Yes
2	$ 12,350.28	$ 5,321.66	2545.58	-14.12	-11.62%	above	Yes	Yes	Yes
3	$ 12,410.68	$ 5,312.33	2485.18	-4.79	-16.30%	above	Yes	Yes	Yes
5	$ 14,412.64	$ 5,320.14	483.22	-12.60	-3.05%	above	Yes	Yes	Yes
6	$ 14,895.85	$ 5,307.54	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 14,956.26	$ 5,297.76	-60.40	9.78	15.78%	below	Yes	Yes	Yes
4	$ 17,855.22	$ 5,293.20	-2959.36	14.34	-12.26%	below	No	No	No
9	$ 19,233.15	$ 5,307.54	-4337.30	0.00	N/A (-∞)	below	No	No	No
10	$ 19,716.37	$ 5,294.94	-4820.52	12.60	-15.02%	below	No	No	No
11	$ 19,776.77	$ 5,285.61	-4880.92	21.93	-12.61%	below	No	No	No
8	$ 20,400.80	$ 5,279.08	-5504.94	28.45	-11.96%	below	No	No	No
13	$ 21,640.61	$ 5,299.06	-6744.75	8.48	-18.04%	below	No	No	No
14	$ 22,123.83	$ 5,286.46	-7227.97	21.08	-14.54%	below	No	No	No
15	$ 22,184.23	$ 5,277.35	-7288.37	30.19	-12.98%	below	No	No	No
12	$ 25,221.31	$ 5,266.93	-10325.46	40.60	-13.22%	below	No	No	No
16	$ 27,628.77	$ 5,258.67	-12732.91	48.86	-13.33%	below	No	No	No

Incremental Analysis			San Antonio - Small Building				MARR = 0.4%
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Compared to Configuration ____**	**Rate of Return (iRR)**	**Better than Previous**
0	0	$ 6,626.53					
1	$ 11,867.06	$ 5,344.45	-11867.06	1282.08	0	9.75%	Yes
2	$ 12,350.28	$ 5,321.66	-483.22	22.80	1	1.31%	Yes
3	**$ 12,410.68**	**$ 5,312.33**	**-60.40**	**9.33**	**2**	**14.97%**	**Yes**
5	$ 14,412.64	$ 5,320.14	-2001.96	-7.81	3	N/A	No
6	$ 14,895.85	$ 5,307.54	-2485.18	4.79	3	-16.30%	No
7	$ 14,956.26	$ 5,297.76	-2545.58	14.57	3	-11.47%	No
4	$ 17,855.22	$ 5,293.20	-5444.54	19.13	3	-13.72%	No
9	$ 19,233.15	$ 5,307.54	-6822.48	4.79	3	-20.29%	No
10	$ 19,716.37	$ 5,294.94	-7305.69	17.39	3	-15.42%	No
11	$ 19,776.77	$ 5,285.61	-7366.10	26.72	3	-13.58%	No
8	$ 20,400.80	$ 5,279.08	-7990.12	33.24	3	-12.96%	No
13	$ 21,640.61	$ 5,299.06	-9229.93	13.27	3	-17.50%	No
14	$ 22,123.83	$ 5,286.46	-9713.15	25.87	3	-14.94%	No
15	$ 22,184.23	$ 5,277.35	-9773.55	34.98	3	-13.64%	No
12	$ 25,221.31	$ 5,266.93	-12810.63	45.39	3	-13.69%	No
16	$ 27,628.77	$ 5,258.67	-15218.09	53.65	3	-13.71%	No

		San Antonio Small Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	***** **3**	7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(6) JB San Antonio, TX – Large Building

Compared to Baseline (No Insulation)			San Antonio - Large Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 26,707.81			
1	$ 15,071.04	$ 21,521.54	-15071.04	5186.27	34.39%
2	$ 16,697.82	$ 21,477.28	-16697.82	5230.53	31.29%
3	$ 16,901.16	$ 21,442.36	-16901.16	5265.46	31.12%
5	$ 17,382.89	$ 21,445.18	-17382.89	5262.64	30.23%
6	$ 19,009.67	$ 21,401.35	-19009.67	5306.46	27.85%
7	$ 19,213.01	$ 21,366.21	-19213.01	5341.61	27.74%
9	$ 21,760.80	$ 21,384.21	-21760.80	5323.60	24.36%
10	$ 23,387.58	$ 21,340.61	-23387.58	5367.21	22.81%
11	$ 23,590.92	$ 21,306.33	-23590.92	5401.48	22.76%
13	$ 23,947.21	$ 21,347.12	-23947.21	5360.70	22.24%
14	$ 25,573.99	$ 21,303.73	-25573.99	5404.09	20.95%
15	$ 25,777.33	$ 21,269.88	-25777.33	5437.93	20.91%
4	$ 35,230.49	$ 21,373.58	-35230.49	5334.23	14.64%
8	$ 37,542.34	$ 21,298.52	-37542.34	5409.29	13.85%
12	$ 41,920.25	$ 21,240.16	-41920.25	5467.65	12.33%
16	$ 44,106.66	$ 21,203.72	-44106.66	5504.10	11.69%

Compared to Standard				San Antonio - Large Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 15,071.04	$ 21,521.54	3938.63	-120.19	-1.98%	above	Yes	Yes	Yes
2	$ 16,697.82	$ 21,477.28	2311.85	-75.93	-1.46%	above	Yes	Yes	Yes
3	$ 16,901.16	$ 21,442.36	2108.50	-41.00	-4.92%	above	Yes	Yes	Yes
5	$ 17,382.89	$ 21,445.18	1626.78	-43.82	-2.84%	above	Yes	Yes	Yes
6	$ 19,009.67	$ 21,401.35	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 19,213.01	$ 21,366.21	-203.35	35.15	16.94%	below	Yes	Yes	Yes
9	$ 21,760.80	$ 21,384.21	-2751.13	17.14	-11.07%	below	No	No	No
10	$ 23,387.58	$ 21,340.61	-4377.91	60.74	-6.90%	below	No	No	No
11	$ 23,590.92	$ 21,306.33	-4581.26	95.02	-4.52%	below	No	No	No
13	$ 23,947.21	$ 21,347.12	-4937.54	54.24	-8.18%	below	No	No	No
14	$ 25,573.99	$ 21,303.73	-6564.32	97.63	-6.51%	below	No	No	No
15	$ 25,777.33	$ 21,269.88	-6767.67	131.47	-4.93%	below	No	No	No
4	$ 35,230.49	$ 21,373.58	-16220.82	27.77	-16.79%	below	No	No	No
8	$ 37,542.34	$ 21,298.52	-18532.67	102.83	-11.62%	below	No	No	No
12	$ 41,920.25	$ 21,240.16	-22910.58	161.19	-10.47%	below	No	No	No
16	$ 44,106.66	$ 21,203.72	-25096.99	197.64	-9.91%	below	No	No	No

Incremental Analysis			San Antonio - Large Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	0	$26,707.81					
1	$ 15,071.04	$21,521.54	-15071.04	5186.27	0	34.39%	Yes
2	$ 16,697.82	$21,477.28	-1626.78	44.26	1	-2.77%	No
3	**$ 16,901.16**	**$21,442.36**	**-1830.12**	**79.18**	**1**	**0.61%**	**Yes**
5	$ 17,382.89	$21,445.18	-481.73	-2.82	3	N/A	No
6	$ 19,009.67	$21,401.35	-2108.50	41.00	3	-4.92%	No
7	$ 19,213.01	$21,366.21	-2311.85	76.15	3	-1.44%	No
9	$ 21,760.80	$21,384.21	-4859.64	58.14	3	-7.72%	No
10	$ 23,387.58	$21,340.61	-6486.41	101.75	3	-6.20%	No
11	$ 23,590.92	$21,306.33	-6689.76	136.02	3	-4.65%	No
13	$ 23,947.21	$21,347.12	-7046.05	95.24	3	-7.05%	No
14	$ 25,573.99	$21,303.73	-8672.82	138.63	3	-6.09%	No
15	$ 25,777.33	$21,269.88	-8876.17	172.47	3	-4.93%	No
4	$ 35,230.49	$21,373.58	-18329.32	68.77	3	-13.43%	No
8	$ 37,542.34	$21,298.52	-20641.18	143.83	3	-10.52%	No
12	$ 41,920.25	$21,240.16	-25019.09	202.19	3	-9.78%	No
16	$ 44,106.66	$21,203.72	-27205.49	238.64	3	-9.36%	No

		San Antonio Large Bldg			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	***** **3**	7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(7) Edwards AFB, CA – Small Building

Compared to Baseline (No Insulation)			California - Small Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 10,421.19			
1	$ 16,994.26	$ 9,169.51	-16994.26	1251.67	5.38%
2	$ 17,496.90	$ 9,146.98	-17496.90	1274.20	5.26%
3	$ 17,559.73	$ 9,130.38	-17559.73	1290.81	5.36%
5	$ 19,845.29	$ 9,146.98	-19845.29	1274.20	4.03%
6	$ 20,347.93	$ 9,124.85	-20347.93	1296.33	3.96%
7	$ 20,410.76	$ 9,108.24	-20410.76	1312.94	4.05%
4	$ 24,441.75	$ 9,097.95	-24441.75	1323.23	2.48%
8	$ 27,292.78	$ 9,076.22	-27292.78	1344.97	1.67%
9	$ 28,464.72	$ 9,127.62	-28464.72	1293.56	1.01%
10	$ 28,967.37	$ 9,106.26	-28967.37	1314.92	1.00%
11	$ 29,030.20	$ 9,089.66	-29030.20	1331.53	1.08%
13	$ 31,629.06	$ 9,115.37	-31629.06	1305.82	0.24%
14	$ 32,131.71	$ 9,094.01	-32131.71	1327.17	0.25%
15	$ 32,194.54	$ 9,077.02	-32194.54	1344.16	0.33%
12	$ 35,912.22	$ 9,057.25	-35912.22	1363.94	-0.39%
16	$ 39,076.56	$ 9,045.39	-39076.56	1375.79	-0.96%

Compared to Standard				California - Small Building				Treasury Notes and Bonds	
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**	**MARR should be _____ iRR to merit selection over comparison**	**MARR 0%**	**MARR 0.4%**	**MARR 6%**
1	$ 16,994.26	$ 9,169.51	3353.68	-44.66	-7.13%	above	Yes	Yes	Yes
2	$ 17,496.90	$ 9,146.98	2851.03	-22.13	-9.98%	above	Yes	Yes	Yes
3	$ 17,559.73	$ 9,130.38	2788.20	-5.52	-16.19%	above	Yes	Yes	Yes
5	$ 19,845.29	$ 9,146.98	502.65	-22.13	0.75%	above	No	No	Yes
6	$ 20,347.93	$ 9,124.85	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 20,410.76	$ 9,108.24	-62.83	16.61	26.36%	below	Yes	Yes	Yes
4	$ 24,441.75	$ 9,097.95	-4093.82	26.90	-10.81%	below	No	No	No
8	$ 27,292.78	$ 9,076.22	-6944.85	48.64	-10.49%	below	No	No	No
9	$ 28,464.72	$ 9,127.62	-8116.79	-2.77	N/A	below	No	No	No
10	$ 28,967.37	$ 9,106.26	-8619.44	18.59	-15.84%	below	No	No	No
11	$ 29,030.20	$ 9,089.66	-8682.27	35.19	-13.08%	below	No	No	No
13	$ 31,629.06	$ 9,115.37	-11281.13	9.48	-19.61%	below	No	No	No
14	$ 32,131.71	$ 9,094.01	-11783.78	30.84	-15.01%	below	No	No	No
15	$ 32,194.54	$ 9,077.02	-11846.61	47.83	-13.10%	below	No	No	No
12	$ 35,912.22	$ 9,057.25	-15564.29	67.60	-12.76%	below	No	No	No
16	$ 39,076.56	$ 9,045.39	-18728.63	79.46	-12.87%	below	No	No	No

Incremental Analysis			California - Small Building				MARR = 0.4%
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Compared to Configuration ____**	**Rate of Return (iRR)**	**Better than Previous**
0	0	$10,421.19					
1	$ 16,994.26	$ 9,169.51	-16994.26	1251.67	0	5.38%	Yes
2	$ 17,496.90	$ 9,146.98	-502.65	22.53	1	0.89%	Yes
3	**$ 17,559.73**	**$ 9,130.38**	**-62.83**	**16.61**	**2**	**26.36%**	**Yes**
5	$ 19,845.29	$ 9,146.98	-2285.56	-16.61	3	N/A	No
6	$ 20,347.93	$ 9,124.85	-2788.20	5.52	3	-16.19%	No
7	$ 20,410.76	$ 9,108.24	-2851.03	22.13	3	-9.98%	No
4	$ 24,441.75	$ 9,097.95	-6882.02	32.42	3	-12.39%	No
8	$ 27,292.78	$ 9,076.22	-9733.05	54.16	3	-11.61%	No
9	$ 28,464.72	$ 9,127.62	-10904.99	2.75	3	-23.99%	No
10	$ 28,967.37	$ 9,106.26	-11407.64	24.11	3	-15.92%	No
11	$ 29,030.20	$ 9,089.66	-11470.47	40.72	3	-13.68%	No
13	$ 31,629.06	$ 9,115.37	-14069.33	15.01	3	-18.69%	No
14	$ 32,131.71	$ 9,094.01	-14571.98	36.36	3	-15.22%	No
15	$ 32,194.54	$ 9,077.02	-14634.81	53.35	3	-13.56%	No
12	$ 35,912.22	$ 9,057.25	-18352.49	73.13	3	-13.16%	No
16	$ 39,076.56	$ 9,045.39	-21516.83	84.98	3	-13.20%	No

		California - Small Building			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	***** 3	7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(8) Edwards AFB, CA – Large Building

Compared to Baseline (No Insulation)			California - Large Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 42,283.71			
1	$21,470.39	$ 35,453.21	-21470.39	6830.50	31.78%
2	$23,162.57	$ 35,343.17	-23162.57	6940.54	29.92%
3	$23,374.09	$ 35,258.46	-23374.09	7025.25	30.01%
5	$24,059.65	$ 35,277.85	-24059.65	7005.85	29.07%
6	$25,751.83	$ 35,170.58	-25751.83	7113.13	27.56%
7	$25,963.35	$ 35,088.25	-25963.35	7195.46	27.65%
9	$31,887.67	$ 35,148.42	-31887.67	7135.29	22.23%
10	$33,579.85	$ 35,043.13	-33579.85	7240.58	21.39%
11	$33,791.37	$ 34,961.58	-33791.37	7322.13	21.50%
13	$34,761.47	$ 35,074.79	-34761.47	7208.92	20.54%
14	$36,453.65	$ 34,969.90	-36453.65	7313.81	19.85%
15	$36,665.17	$ 34,890.33	-36665.17	7393.38	19.95%
4	$46,542.76	$ 35,092.21	-46542.76	7191.50	14.98%
8	$49,132.02	$ 34,925.96	-49132.02	7357.75	14.46%
12	$56,960.05	$ 34,802.46	-56960.05	7481.25	12.43%
16	$59,833.85	$ 34,732.79	-59833.85	7550.92	11.85%

Compared to Standard				California - Large Building				Treasury Notes and Bonds	
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**	**MARR should be _____ iRR to merit selection over comparison**	**MARR 0%**	**MARR 0.4%**	**MARR 6%**
1	$ 21,470.39	$ 35,453.21	4281.44	-282.62	4.29%	above	Yes	Yes	Yes
2	$ 23,162.57	$ 35,343.17	2589.26	-172.58	4.39%	above	Yes	Yes	Yes
3	$ 23,374.09	$ 35,258.46	2377.74	-87.88	-0.60%	above	Yes	Yes	Yes
5	$ 24,059.65	$ 35,277.85	1692.18	-107.27	3.91%	above	Yes	Yes	Yes
6	$ 25,751.83	$ 35,170.58	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 25,963.35	$ 35,088.25	-211.52	82.33	38.91%	below	Yes	Yes	Yes
9	$ 31,887.67	$ 35,148.42	-6135.84	22.17	-13.60%	below	No	No	No
10	$ 33,579.85	$ 35,043.13	-7828.02	127.46	-5.98%	below	No	No	No
11	$ 33,791.37	$ 34,961.58	-8039.55	209.00	-3.07%	below	No	No	No
13	$ 34,761.47	$ 35,074.79	-9009.64	95.79	-8.36%	below	No	No	No
14	$ 36,453.65	$ 34,969.90	-10701.82	200.69	-5.14%	below	No	No	No
15	$ 36,665.17	$ 34,890.33	-10913.35	280.25	-3.15%	below	No	No	No
4	$ 46,542.76	$ 35,092.21	-20790.94	78.38	-13.41%	above	No	No	No
8	$ 49,132.02	$ 34,925.96	-23380.20	244.63	-8.44%	below	No	No	No
12	$ 56,960.05	$ 34,802.46	-31208.22	368.13	-7.80%	below	No	No	No
16	$ 59,833.85	$ 34,732.79	-34082.02	437.79	-7.33%	below	No	No	No

Incremental Analysis			California - Large Building				MARR = 0.4%
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Compared to Configuration ____**	**Rate of Return (iRR)**	**Better than Previous**
0	0	$42,283.71					
1	$ 21,470.39	$19,430.85	-21470.39	22852.86	0	106.44%	Yes
2	$ 23,162.57	$19,370.54	-1692.18	60.31	1	-0.87%	No
3	$ 23,374.09	$19,324.11	**-1903.70**	**106.74**	**1**	**2.79%**	**Yes**
5	$ 24,059.65	$19,334.74	-685.55	-10.63	3	N/A	No
6	$ 25,751.83	$19,275.95	-2377.74	48.16	3	-4.67%	No
7	$ 25,963.35	$19,230.82	-2589.26	93.29	3	-0.79%	No
9	$ 31,887.67	$19,263.80	-8513.58	60.31	3	-10.44%	No
10	$ 33,579.85	$19,206.09	-10205.76	118.02	3	-7.90%	No
11	$ 33,791.37	$19,161.40	-10417.28	162.71	3	-6.22%	No
13	$ 34,761.47	$19,223.45	-11387.38	100.66	3	-9.32%	No
14	$ 36,453.65	$19,165.96	-13079.56	158.15	3	-7.66%	No
15	$ 36,665.17	$19,122.35	-13291.08	201.76	3	-6.39%	No
4	$ 46,542.76	$19,232.99	-23168.67	91.12	3	-13.22%	No
8	$ 49,132.02	$19,141.88	-25757.93	182.23	3	-10.44%	No
12	$ 56,960.05	$19,074.19	-33585.96	249.92	3	-10.19%	No
16	$ 59,833.85	$19,036.01	-36459.75	288.10	3	-9.89%	No

		California - Large Building			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	***** **3**	7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(9) Ellsworth AFB, SD – Small Building

Compared to Baseline (No Insulation)			South Dakota - Small Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	$ -	$ 19,016.63			
1	$ 10,997.00	$ 9,395.13	-10997.00	9621.50	87.49%
2	$ 11,510.60	$ 9,254.52	-11510.60	9762.10	84.81%
3	$ 11,574.80	$ 9,141.13	-11574.80	9875.50	85.32%
5	$ 13,632.06	$ 9,194.55	-13632.06	9822.08	72.05%
6	$ 14,145.67	$ 9,061.83	-14145.67	9954.79	70.37%
7	$ 14,209.87	$ 8,960.31	-14209.87	10056.32	70.77%
4	$ 16,938.16	$ 8,939.07	-16938.16	10077.56	59.50%
9	$ 17,502.61	$ 9,027.01	-17502.61	9989.61	57.07%
10	$ 18,016.21	$ 8,900.55	-18016.21	10116.08	56.15%
11	$ 18,080.41	$ 8,803.50	-18080.41	10213.13	56.49%
8	$ 19,573.22	$ 8,767.55	-19573.22	10249.07	52.36%
13	$ 19,832.01	$ 8,923.21	-19832.01	10093.42	50.89%
14	$ 20,345.62	$ 8,798.80	-20345.62	10217.83	50.22%
15	$ 20,409.82	$ 8,703.10	-20409.82	10313.52	50.53%
12	$ 23,443.77	$ 8,615.65	-23443.77	10400.98	44.36%
16	$ 25,773.18	$ 8,525.56	-25773.18	10491.07	40.70%

Compared to Standard				South Dakota - Small Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be ____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 10,997.00	$ 9,395.13	3148.67	-333.29	9.49%	above	No	No	No
2	$ 11,510.60	$ 9,254.52	2635.06	-192.69	5.30%	above	No	No	Yes
3	$ 11,574.80	$ 9,141.13	2570.86	-79.29	-1.91%	above	Yes	Yes	Yes
5	$ 13,632.06	$ 9,194.55	513.60	-132.71	25.76%	above	No	No	No
6	$ 14,145.67	$ 9,061.83	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 14,209.87	$ 8,960.31	-64.20	101.53	158.14%	below	Yes	Yes	Yes
4	$ 16,938.16	$ 8,939.07	-2792.49	122.77	0.74%	below	Yes	Yes	No
9	$ 17,502.61	$ 9,027.01	-3356.94	34.82	-8.49%	below	No	No	No
10	$ 18,016.21	$ 8,900.55	-3870.54	161.28	0.32%	below	Yes	No	No
11	$ 18,080.41	$ 8,803.50	-3934.75	258.34	4.24%	below	Yes	Yes	No
8	$ 19,573.22	$ 8,767.55	-5427.56	294.28	2.49%	below	Yes	Yes	No
13	$ 19,832.01	$ 8,923.21	-5686.35	138.63	-3.49%	below	No	No	No
14	$ 20,345.62	$ 8,798.80	-6199.95	263.03	0.46%	below	Yes	Yes	No
15	$ 20,409.82	$ 8,703.10	-6264.15	358.73	2.97%	below	Yes	Yes	No
12	$ 23,443.77	$ 8,615.65	-9298.10	446.19	1.45%	below	Yes	Yes	No
16	$ 25,773.18	$ 8,525.56	-11627.51	536.28	1.13%	below	Yes	Yes	No

Incremental Analysis			South Dakota - Small Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	$ -	$19,016.63					
1	$ 10,997.00	$ 9,395.13	-10997.00	9621.50	0	87.49%	Yes
2	$ 11,510.60	$ 9,254.52	-513.60	140.60	1	27.31%	Yes
3	$ 11,574.80	$ 9,141.13	-64.20	113.40	2	176.63%	Yes
5	$ 13,632.06	$ 9,194.55	-2057.26	-53.42	3	N/A	No
6	$ 14,145.67	$ 9,061.83	-2570.86	79.29	3	-1.91%	No
7	**$ 14,209.87**	**$ 8,960.31**	**-2635.06**	**180.82**	**3**	**4.67%**	**Yes**
4	$ 16,938.16	$ 8,939.07	-2728.29	21.24	7	-9.97%	No
9	$ 17,502.61	$ 9,027.01	-3292.74	-66.71	7	N/A	No
10	$ 18,016.21	$ 8,900.55	-3806.34	59.76	7	-6.19%	No
11	$ 18,080.41	$ 8,803.50	-3870.54	156.81	7	0.10%	No
8	$ 19,573.22	$ 8,767.55	-5363.36	192.75	7	-0.81%	No
13	$ 19,832.01	$ 8,923.21	-5622.15	37.10	7	-10.79%	No
14	$ 20,345.62	$ 8,798.80	-6135.75	161.50	7	-2.99%	No
15	$ 20,409.82	$ 8,703.10	-6199.95	257.20	7	0.28%	No
12	$ 23,443.77	$ 8,615.65	-9233.90	344.66	7	-0.53%	No
16	$ 25,773.18	$ 8,525.56	-11563.31	434.75	7	-0.47%	No

		South Dakota - Small Building			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	***** 7	11	15
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(10) Ellsworth AFB, SD – Large Building

Compared to Baseline (No Insulation)			South Dakota - Large Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 55,775.24			
1	$ 14,005.05	$ 34,890.69	-14005.05	20884.56	149.12%
2	$ 15,734.13	$ 34,667.20	-15734.13	21108.04	#NUM!
3	$ 15,950.26	$ 34,492.78	-15950.26	21282.46	133.43%
5	$ 16,398.17	$ 34,516.89	-16398.17	21258.35	129.64%
6	$ 18,127.25	$ 34,294.26	-18127.25	21480.99	#NUM!
7	$ 18,343.38	$ 34,120.69	-18343.38	21654.56	118.05%
9	$ 19,913.33	$ 34,196.98	-19913.33	21578.27	108.36%
10	$ 21,642.41	$ 33,975.76	-21642.41	21799.48	100.73%
11	$ 21,858.55	$ 33,802.76	-21858.55	21972.49	100.52%
13	$ 22,028.86	$ 33,996.18	-22028.86	21779.06	98.87%
14	$ 23,757.94	$ 33,775.25	-23757.94	22000.00	92.60%
15	$ 23,974.07	$ 33,603.10	-23974.07	22172.15	92.48%
4	$ 34,006.29	$ 34,143.37	-34006.29	21631.87	63.61%
8	$ 36,399.40	$ 33,773.26	-36399.40	22001.98	60.45%
12	$ 39,914.57	$ 33,457.32	-39914.57	22317.93	55.91%
16	$ 42,030.10	$ 33,257.94	-42030.10	22517.30	53.57%

Compared to Standard				South Dakota - Large Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 14,005.05	$ 34,890.69	4122.20	-596.43	13.91%	above	No	No	No
2	$ 15,734.13	$ 34,667.20	2393.12	-372.95	15.12%	above	No	No	No
3	$ 15,950.26	$ 34,492.78	2176.98	-198.53	7.69%	above	No	No	No
5	$ 16,398.17	$ 34,516.89	1729.08	-222.63	12.14%	above	No	No	No
6	$ 18,127.25	$ 34,294.26	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 18,343.38	$ 34,120.69	-216.13	173.57	80.31%	below	Yes	Yes	Yes
9	$ 19,913.33	$ 34,196.98	-1786.08	97.28	2.53%	below	Yes	Yes	No
10	$ 21,642.41	$ 33,975.76	-3515.16	318.50	7.61%	below	Yes	Yes	Yes
11	$ 21,858.55	$ 33,802.76	-3731.30	491.50	12.48%	below	Yes	Yes	Yes
13	$ 22,028.86	$ 33,996.18	-3901.61	298.08	5.75%	below	Yes	Yes	No
14	$ 23,757.94	$ 33,775.25	-5630.69	519.01	7.81%	below	Yes	Yes	Yes
15	$ 23,974.07	$ 33,603.10	-5846.83	691.16	10.94%	below	Yes	Yes	Yes
4	$ 34,006.29	$ 34,143.37	-15879.04	150.88	-8.95%	below	No	No	No
8	$ 36,399.40	$ 33,773.26	-18272.16	520.99	-2.45%	below	No	No	No
12	$ 39,914.57	$ 33,457.32	-21787.32	836.94	-0.31%	below	No	No	No
16	$ 42,030.10	$ 33,257.94	-23902.85	1036.32	0.63%	below	Yes	Yes	No

Incremental Analysis			South Dakota - Large Building				MARR = 0.4%
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Compared to Configuration ____**	**Rate of Return (iRR)**	**Better than Previous**
0	0	$55,775.24					
1	$ 14,005.05	$34,890.69	-14005.05	20884.56	0	149.12%	Yes
2	$ 15,734.13	$34,667.20	-1729.08	223.49	1	12.20%	Yes
3	$ 15,950.26	$34,492.78	-216.13	174.42	2	80.70%	Yes
5	$ 16,398.17	$34,516.89	-447.91	-24.11	3	N/A	No
6	$ 18,127.25	$34,294.26	-2176.98	198.53	3	7.69%	Yes
7	$ 18,343.38	$34,120.69	-216.13	173.57	6	80.31%	Yes
9	$ 19,913.33	$34,196.98	-1569.95	-76.29	7	N/A	No
10	$ 21,642.41	$33,975.76	-3299.03	144.93	7	0.73%	Yes
11	$ 21,858.55	$33,802.76	-216.13	173.00	10	80.04%	Yes
13	$ 22,028.86	$33,996.18	-170.32	-193.42	11	N/A	No
14	$ 23,757.94	$33,775.25	-1899.39	27.51	11	-6.66%	No
15	**$ 23,974.07**	**$33,603.10**	**-2115.53**	**199.66**	**11**	**8.09%**	**Yes**
4	$ 34,006.29	$34,143.37	-10032.21	-540.28	15	N/A	No
8	$ 36,399.40	$33,773.26	-12425.33	-170.17	15	N/A	No
12	$ 39,914.57	$33,457.32	-15940.49	145.78	15	-9.15%	No
16	$ 42,030.10	$33,257.94	-18056.02	345.15	15	-5.02%	No

		South Dakota - Large Building			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	7	11	***** **15**
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(11) Minot AFB, ND – Small Building

Compared to Baseline (No Insulation)			North Dakota - Small Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	$ -	$ 17,357.16			
1	$ 13,951.64	$ 11,199.77	-13951.64	6157.39	44.13%
2	$ 14,492.15	$ 11,022.54	-14492.15	6334.63	43.71%
3	$ 14,559.71	$ 10,882.32	-14559.71	6474.84	44.47%
5	$ 16,828.61	$ 10,953.45	-16828.61	6403.71	38.04%
6	$ 17,369.12	$ 10,770.31	-17369.12	6586.85	37.91%
7	$ 17,436.68	$ 10,632.66	-17436.68	6724.50	38.55%
4	$ 20,827.32	$ 10,601.54	-20827.32	6755.62	32.41%
9	$ 22,746.01	$ 10,726.46	-22746.01	6630.70	29.10%
10	$ 23,286.52	$ 10,541.69	-23286.52	6815.47	29.22%
11	$ 23,354.08	$ 10,388.89	-23354.08	6968.27	29.79%
8	$ 23,704.29	$ 10,339.30	-23704.29	7017.87	29.56%
13	$ 25,535.09	$ 10,574.23	-25535.09	6782.93	26.49%
14	$ 26,075.59	$ 10,383.84	-26075.59	6973.32	26.67%
15	$ 26,143.15	$ 10,234.74	-26143.15	7122.42	27.18%
12	$ 29,621.69	$ 10,115.72	-29621.69	7241.45	24.34%
16	$ 32,410.76	$ 9,971.38	-32410.76	7385.79	22.65%

Compared to Standard				North Dakota - Small Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	$ 13,951.64	$ 11,199.77	3417.48	-429.46	11.79%	above	No	No	No
2	$ 14,492.15	$ 11,022.54	2876.97	-252.22	7.24%	above	No	No	No
3	$ 14,559.71	$ 10,882.32	2809.41	-112.01	-0.03%	above	Yes	Yes	Yes
5	$ 16,828.61	$ 10,953.45	540.51	-183.14	33.86%	above	No	No	No
6	$ 17,369.12	$ 10,770.31	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	$ 17,436.68	$ 10,632.66	-67.56	137.65	203.74%	below	Yes	Yes	Yes
4	$ 20,827.32	$ 10,601.54	-3458.20	168.77	1.59%	below	Yes	Yes	No
9	$ 22,746.01	$ 10,726.46	-5376.89	43.85	-9.73%	below	No	No	No
10	$ 23,286.52	$ 10,541.69	-5917.40	228.62	-0.27%	below	No	No	No
11	$ 23,354.08	$ 10,388.89	-5984.96	381.42	3.96%	below	Yes	Yes	No
8	$ 23,704.29	$ 10,339.30	-6335.17	431.02	4.59%	below	Yes	Yes	No
13	$ 25,535.09	$ 10,574.23	-8165.97	196.08	-3.59%	below	No	No	No
14	$ 26,075.59	$ 10,383.84	-8706.47	386.47	0.82%	below	Yes	Yes	No
15	$ 26,143.15	$ 10,234.74	-8774.03	535.57	3.56%	below	Yes	Yes	No
12	$ 29,621.69	$ 10,115.72	-12252.57	654.60	2.36%	below	Yes	Yes	No
16	$ 32,410.76	$ 9,971.38	-15041.64	798.94	2.31%	below	Yes	Yes	No

Incremental Analysis			North Dakota - Small Building				MARR = 0.4%
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Compared to Configuration ____	Rate of Return (iRR)	Better than Previous
0	$ -	$17,357.16					
1	$ 13,951.64	$11,199.77	-13951.64	6157.39	0	44.13%	Yes
2	$ 14,492.15	$11,022.54	-540.51	177.24	1	32.76%	Yes
3	$ 14,559.71	$10,882.32	-67.56	140.21	2	207.53%	Yes
5	$ 16,828.61	$10,953.45	-2268.90	-71.13	3	N/A	No
6	$ 17,369.12	$10,770.31	-2809.41	112.01	3	-0.03%	No
7	$ 17,436.68	$10,632.66	-2876.97	249.66	3	7.12%	Yes
4	$ 20,827.32	$10,601.54	-3390.64	31.12	7	-9.13%	No
9	$ 22,746.01	$10,726.46	-5309.33	-93.80	7	N/A	No
10	$ 23,286.52	$10,541.69	-5849.84	90.97	7	-6.25%	No
11	$ 23,354.08	$10,388.89	-5917.40	243.77	7	0.23%	No
8	$ 23,704.29	$10,339.30	-6267.61	293.37	7	1.25%	Yes
13	$ 25,535.09	$10,574.23	-1830.79	-234.93	8	N/A	No
14	$ 26,075.59	$10,383.84	-2371.30	-44.55	8	N/A	No
15	**$ 26,143.15**	**$10,234.74**	**-2438.86**	**104.55**	**8**	**0.54%**	**Yes**
12	$ 29,621.69	$10,115.72	-3478.54	119.03	15	-1.17%	No
16	$ 32,410.76	$ 9,971.38	-6267.61	263.37	15	0.38%	No

		North Dakota - Small Building			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	7	11	***** **15**
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

(12) Minot AFB, ND – Large Building

Compared to Baseline (No Insulation)			North Dakota - Large Building		
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Rate of Return (iRR)**
0	0	$ 61,859.55			
1	17702.10	$ 37,997.65	-17702.10	23861.90	#NUM!
2	19521.74	$ 37,742.12	-19521.74	24117.44	123.54%
3	19749.19	$ 37,543.02	-19749.19	24316.53	123.13%
5	20314.91	$ 37,572.80	-20314.91	24286.75	119.55%
6	22134.55	$ 37,318.40	-22134.55	24541.15	110.87%
7	22362.01	$ 37,119.02	-22362.01	24740.53	110.64%
9	25688.99	$ 37,207.79	-25688.99	24651.76	95.96%
10	27508.63	$ 36,953.96	-27508.63	24905.59	90.54%
11	27736.09	$ 36,755.72	-27736.09	25103.84	90.51%
13	28221.98	$ 36,977.22	-28221.98	24882.34	88.17%
14	30041.62	$ 36,723.95	-30041.62	25135.60	83.67%
15	30269.08	$ 36,526.56	-30269.08	25333.00	83.69%
4	40849.43	$ 37,142.85	-40849.43	24716.71	60.51%
8	43462.25	$ 36,720.83	-43462.25	25138.72	57.84%
12	48836.33	$ 36,358.94	-48836.33	25500.61	52.22%
16	51369.31	$ 36,130.64	-51369.31	25728.92	50.08%

Compared to Standard				North Dakota - Large Building				Treasury Notes and Bonds	
Number	Initial Cost	Annual Cost	Acquisition Savings	Annual Cost Savings	Rate of Return (iRR)	MARR should be _____ iRR to merit selection over comparison	MARR 0%	MARR 0.4%	MARR 6%
1	17702.10	$ 37,997.65	4432.46	-679.25	14.84%	above	No	No	No
2	19521.74	$ 37,742.12	2612.82	-423.72	15.80%	above	No	No	No
3	19749.19	$ 37,543.02	2385.36	-224.62	8.06%	above	No	No	No
5	20314.91	$ 37,572.80	1819.64	-254.40	13.37%	above	No	No	No
6	22134.55	$ 37,318.40	0.00	0.00	0.00%	N/A	Indifferent	Indifferent	Indifferent
7	22362.01	$ 37,119.02	-227.46	199.38	87.66%	below	Yes	Yes	Yes
9	25688.99	$ 37,207.79	-3554.44	110.61	-1.84%	below	No	No	No
10	27508.63	$ 36,953.96	-5374.08	364.44	4.55%	below	Yes	Yes	No
11	27736.09	$ 36,755.72	-5601.53	562.68	8.84%	below	Yes	Yes	Yes
13	28221.98	$ 36,977.22	-6087.43	341.18	2.78%	below	Yes	Yes	No
14	30041.62	$ 36,723.95	-7907.07	594.45	5.59%	below	Yes	Yes	No
15	30269.08	$ 36,526.56	-8134.52	791.84	8.45%	below	Yes	Yes	Yes
4	40849.43	$ 37,142.85	-18714.88	175.56	-9.01%	below	No	No	No
8	43462.25	$ 36,720.83	-21327.69	597.57	-2.57%	below	No	No	No
12	48836.33	$ 36,358.94	-26701.77	959.46	-0.81%	below	No	No	No
16	51369.31	$ 36,130.64	-29234.76	1187.76	0.12%	below	Yes	No	No

Incremental Analysis			North Dakota - Large Building				MARR = 0.4%
Number	**Initial Cost**	**Annual Cost**	**Acquisition Savings**	**Annual Cost Savings**	**Compared to Configuration ____**	**Rate of Return (iRR)**	**Better than Previous**
0	0	$61,859.55					
1	17702.10	$37,997.65	-17702.10	23861.90	0	#NUM!	Yes
2	19521.74	$37,742.12	-1819.64	255.53	1	13.44%	Yes
3	19749.19	$37,543.02	-227.46	199.10	2	87.53%	Yes
5	20314.91	$37,572.80	-565.72	-29.78	3	N/A	No
6	22134.55	$37,318.40	-2385.36	224.62	3	8.06%	Yes
7	22362.01	$37,119.02	-227.46	199.38	6	87.66%	Yes
9	25688.99	$37,207.79	-3326.98	-88.77	7	N/A	No
10	27508.63	$36,953.96	-5146.62	165.06	7	-1.63%	No
11	27736.09	$36,755.72	-5374.08	363.31	7	4.52%	Yes
13	28221.98	$36,977.22	-485.89	-221.50	11	N/A	No
14	30041.62	$36,723.95	-2305.53	31.76	11	-6.94%	No
15	30269.08	$36,526.56	**-2532.99**	**229.16**	**11**	**7.60%**	**Yes**
4	40849.43	$37,142.85	-10580.35	-616.29	15	N/A	No
8	43462.25	$36,720.83	-13193.17	-194.27	15	N/A	No
12	48836.33	$36,358.94	-18567.25	167.61	15	-9.21%	No
16	51369.31	$36,130.64	-21100.24	395.92	15	-5.14%	No

		North Dakota - Large Building			
		Below	Standard	Above	Sig Above
	Insulation	R-30	R-38	R-49	R-60
Sig Above	R-21	4	8	12	16
Above	R-15	3	7	11	***** **15**
Standard	R-13	2	6	10	14
Below	R-11	1	5	9	13

References

[1] W. Commission, “Report of the World Commission on Environment and Development : Our Common Future Acronyms and Note on Terminology Chairman ’ s Foreword,” 1987.

[2] Department of Defense, “DoD Climate Change Adaptation Roadmap,” 2014.

[3] Department of Defense, “Climate Change: National Security Implications,” no. July, pp. 1–14, 2015.

[4] T. Theis and J. Tomkin, *Sustainability : A Comprehensive Foundation*. .

[5] G. H. Kats, “Green Building Costs and Financial Benefits,” *Massachusetts Technol. Collab.*, pp. 2–5, 2003.

[6] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, “ISO 55000 — Asset management — Overview, principles and terminology,” *Int. Organ. Stand.*, 2014.

[7] M. N. Grussing and L. R. Marrano, “Building Component Lifecycle Repair/Replacement Model for Institutional Facility Management,” *Comput. Civ. Eng.*, pp. 550–557, 2007.

[8] G. D. Daan Schraven, Andreas Hartmann, “Effectiveness of infrastructure asset management: challenges for public agencies: Built Environment Project and Asset Management: Vol 1, No 1,” *Built Environ. Proj. Asset Manag.*, vol. 1, no. 1, pp. 61–74, 2011.

[9] T. O. of the A. S. of D. for E. I. and Environment, “2018 DoD Installation Energy Energy Strategy,” 2018. [Online]. Available: https://www.acq.osd.mil/eie/IE/FEP_index.html.

[10] United States Air Force, “Energy Flight Plan,” 2017.

[11] S. I. Construction, “CHAPTER 169-MILITARY CONSTRUCTION AND MILITARY FAMILY HOUSING,” no. 1, pp. 1–5, 2019.

[12] V. Granadeiro, J. P. Duarte, J. R. Correia, and V. M. S. Leal, “Building envelope shape design in early stages of the design process: Integrating architectural design systems and energy simulation,” *Autom. Constr.*, 2013.

[13] M. J. Moran and H. N. Shapiro, *Fundamentals of engineering thermodynamics*. 2008.

[14] C. Biserni and M. Garai, “First and second law analysis applied to building envelope: A theoretical approach on the potentiality of Bejan’s theory,” *Energy Reports*, vol. 1,

pp. 181–183, 2015.

[15] A. Scherba, D. J. Sailor, T. N. Rosenstiel, and C. C. Wamser, “Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment,” *Build. Environ.*, 2011.

[16] J. F. Straube and E. F. Burnett, “Building Science for Building Enclosures,” no. Figure 1, 2005.

[17] S. K. Sharma, “Zero energy building envelope components: A review,” *Int. J. Eng. Res. Appl.*, vol. 3, no. 2, pp. 662–675, 2013.

[18] M. S. Mohsen and B. A. Akash, “Some prospects of energy savings in buildings,” *Energy Convers. Manag.*, 2001.

[19] S. A. Al-Sanea, “Evaluation of Heat Transfer Characteristics of Building Wall Elements,” *J. King Saud Univ. - Eng. Sci.*, 2000.

[20] D. J. Sailor, “A green roof model for building energy simulation programs,” *Energy Build.*, 2008.

[21] T. M. I. Mahlia, B. N. Taufiq, Ismail, and H. H. Masjuki, “Correlation between thermal conductivity and the thickness of selected insulation materials for building wall,” *Energy Build.*, 2007.

[22] K. A. Al-Sallal, “Comparison between polystyrene and fiberglass roof insulation in warm and cold climates,” *Renew. Energy*, 2003.

[23] J. W. Lee, H. J. Jung, J. Y. Park, J. B. Lee, and Y. Yoon, “Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements,” *Renew. Energy*, 2013.

[24] M. Lawton, P. Roppel, D. Fookes, A. Teasdale, and D. Schoonhoven, “Real R-value of exterior insulated wall assemblies,” *Proc. BEST2 Conf. Build. Enclos. Sci. Technol.*, p. 26, 2010.

[25] E. Efficient *et al.*, “Thermal Performance of Insulating Window Systems,” 2011.

[26] M. S. Al-Homoud, “Performance characteristics and practical applications of common building thermal insulation materials,” *Build. Environ.*, vol. 40, no. 3, pp. 353–366, 2005.

[27] G. Anandarajah, P. Ekins, and N. Strachan, “Pathways to a low carbon economy,” in *Energy 2050: Making the Transition to a Secure Low Carbon Energy System*, 2012.

[28] R. Baetens, B. P. Jelle, and A. Gustavsen, “Aerogel insulation for building applications: A state-of-the-art review,” *Energy and Buildings*. 2011.

[29] F. H. Abanda and L. Byers, “An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling),” *Energy*, 2016.

[30] Y. Sun, L. Gu, C. F. J. Wu, and G. Augenbroe, “Exploring HVAC system sizing under uncertainty,” *Energy Build.*, 2014.

[31] S. B. Sadineni, S. Madala, and R. F. Boehm, “Passive building energy savings: A review of building envelope components,” *Renewable and Sustainable Energy Reviews*. 2011.

[32] A. E. Ben-Nakhi, “Minimizing thermal bridging through window systems in buildings of hot regions,” *Appl. Therm. Eng.*, 2002.

[33] P. E. Totten, S. M. O’Brien, and M. Pazera, “The Effects of Thermal Bridging at Interface Conditions,” *Build. Enclos. Sci. Technol. (BEST 1) Conf.*, 2008.

[34] A. Hasan, “Optimizing insulation thickness for buildings using life cycle cost,” *Appl. Energy*, 1999.

[35] N. Z. Che-Ghani, N. E. Myeda, and A. S. Ali, “Operations and Maintenance Cost for Stratified Buildings: A Critical Review,” in *MATEC Web of Conferences*, 2016.

[36] C. Thormark, “The effect of material choice on the total energy need and recycling potential of a building,” *Build. Environ.*, 2006.

[37] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith, “Contrasting the capabilities of building energy performance simulation programs,” in *IBPSA 2005 - International Building Performance Simulation Association 2005*, 2005.

[38] Hema Sree Rallapalli, “A Comparison of EnergyPlus and eQUEST Whole Building Energy Simulation Results for a Medium Sized Office Building,” 2010.

[39] S. M. Captain Lee, “DAYLIGHTING STRATEGIES FOR U. S. AIR FORCE OFFICE FACILITIES: ECONOMIC ANALYSIS OF BUILDING ENERGY PERFORMANCE AND LIFECYCLE COST MODELING WITH MONTE CARLO METHOD,” 2009.

[40] R. H. Henninger, M. J. Witte, and D. B. Crawley, “Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100-E200 test suite,” in *Energy and Buildings*, 2004.

[41] N. Fumo, P. Mago, and R. Luck, “Methodology to estimate building energy consumption using EnergyPlus Benchmark Models,” *Energy Build.*, 2010.

[42] K. J. Lomas, H. Eppel, C. J. Martin, and D. P. Bloomfield, “Empirical validation of building energy simulation programs,” *Energy Build.*, 1997.

[43] N. Fumo, “A review on the basics of building energy estimation,” *Renewable and Sustainable Energy Reviews*. 2014.

[44] N. M. Mateus, A. Pinto, and G. C. Da Graça, “Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell,” *Energy Build.*, 2014.

[45] F. Akhlaghi, “Life cycle costing - a tool for decision making,” *Facilities*. 1987.

[46] G. Han, J. Srebric, and E. Enache-Pommer, “Variability of optimal solutions for building components based on comprehensive life cycle cost analysis,” *Energy Build.*, 2014.

[47] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, “Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review,” *Renewable and Sustainable Energy Reviews*. 2014.

[48] A. Ashworth, “Estimating the life expectancies of building components in life-cycle costing calculations,” *Struct. Surv.*, 1996.

[49] U.S. EIA, “U.S. ENERGY INFORMATION ADMINISTRATION SHORT-TERM ENERGY OUTLOOK DATA BROWSER.” [Online]. Available: https://www.eia.gov/outlooks/steo/data/browser/#/?v=21&f=A&s=0&start=2015&end=2020&ctype=linechart&maptype=0&linechart=ESCMU_ENC&map=.

[50] P. Torcellini, M. Deru, B. Griffith, and K. Benne, “DOE Commercial Building Benchmark Models Preprint,” *Contract*, 2008.

[51] D. of Commerce, *North Dakota State Building Code*, vol. 2057, no. 701. 2014.

[52] *North Dakota Century Code Chapter 54-21.3*, no. 1. 2014, pp. 1–5.

[53] *S.D. Codified Laws §11-10-5*. .

[54] D. of Commerce, *Ohio Building Code*, no. June. 2017.

[55] *Virginia Construction Code*. 2018.

[56] *SECTION 110 . 8 – MANDATORY REQUIREMENTS FOR INSULATION ,* vol. 8. 2020, pp. 3–5.

[57] *Section 150.0 – Mandatory Features and Devices*. 2020, pp. 1–13.

[58] R. U. Ayres, “Life cycle analysis: A critique,” *Resour. Conserv. Recycl.*, vol. 14, no. 3–4, pp. 199–223, 1995.

[59] S. K. Durairaj, S. K. Ong, A. Y. C. Nee, and R. B. H. Tan, “Evaluation of life cycle cost analysis methodologies,” *Corp. Environ. Strateg.*, vol. 9, no. 1, pp. 30–39, 2002.

[60] S. Fuller, “WBDG : Life-Cycle Cost Analysis (LCCA) Life-Cycle Cost Analysis (LCCA) WBDG : Life-Cycle Cost Analysis (LCCA),” *Whole Build. Des. Guid.*, no. Lcc, pp. 1–11, 2006.

[61] K.-H. Kim and H.-S. Baik, “Comparative Analysis between RSMeans and Standard Estimating System for Selective Finish Demolition in Remodeling Projects,” *J. Archit. Inst. Korea Struct. Constr.*, vol. 31, no. 3, pp. 73–80, 2015.

[62] M. S. Goldberg, “Discount rates for government investment projects: The economic logic behind OMB circular A-94,” *Eng. Econ.*, 1998.

[63] Office of Management and Budget, “Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses,” no. November 2019, p. 2019, 2014.

[64] T. Eschenbach, “ENGINEERING ECONOMY: APPLYING THEORY TO PRACTICE,” *Eng. Econ.*, 1995.

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Canfield, Michael E., Capt, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/ENV)
2950 Hobson Way
WPAFB, OH 45433-7765

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14. ABSTRACT

The United States Department of Defense (DoD) possesses over 560,000 buildings and structures around the world which require electricity to maintain and operate. The energy costs associated with the operations of these building is approximately $4 billion per year. Sustainable infrastructure management is a crucial opportunity to improve and establish a prudent, manageable, and successful DoD budget. This research identified, modeled, and simulated thermal energy-efficient standards in building construction in order to recognize the best value standards as opportunities for potential cost savings.

EnergyPlus and OpenStudio Building Performance Simulation (BPS) software was used to model the energy flow into and out of buildings to determine the annual energy costs for two prototypical DoD office buildings developed by the Pacific Northwest National Laboratory. The simulation inputs of building size, location, and insulation materials were varied to determine their effects on the energy cost.

The research results indicate that designers, engineers, and policy makers in the Air Force should consider facility life-cycle costs to lower annual facility sustainment costs. Accepting the construction code without performing an energy flow analysis of the facility during the design phase forfeits the opportunity to improve the life-cycle energy cost.

15. SUBJECT TERMS

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